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(54) Controlling method forswitched reluctance motor method and motor having a low peak current

(57) The SR motor (1) includes a stator (3) having a plurality of salient poles (3a), windings (C) wound around the plurality of salient poles (3a) and generating magnetic fields in the plurality of salient poles (3a), and a rotor (2) having another plurality of salient poles (2a), a number of the salient poles of the rotor being determined depending upon a number of the salient poles of the stator. A supply mode for supplying power from a power supply to the windings (C), a reflux mode for setting both terminals (T1, T2) of the windings (C) to an identical potential, and a regenerative mode for recovering electromotive force generated in the windings (C) into the power supply are executed as the rotor (2) rotates. The reflux mode and the regenerative mode are preferably repeated in a period during which the inductance of the windings (C) is reduced as the rotor (2) rotates.

FIG. 5A

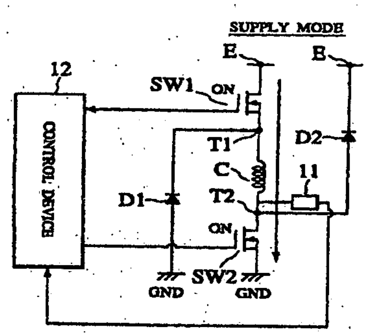
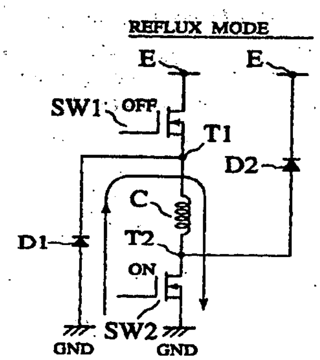


FIG. 5C



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Description

[0001] The present invention relates to an improved technology of an SR motor (switched reluctance motor).

[0002] The SR motor has been known as a motor of the type that does not employ the magnet. Such SR motor is constructed by arranging a stator, in which a plurality of inwardly projecting salient poles are formed integrally with a cylindrical yoke, and a rotor, which has a plurality of outwardly projecting salient poles, on the same shaft and then fitting winding coils on the salient poles of the stator.

[0003] The numbers of the salient poles of the rotor and the salient poles of the stator are set to an even number respectively not to constitute a multiple relationship mutually. For example, the number of the salient poles of the rotor is four while the number of the salient poles of the stator is six, the number of the salient poles of the rotor is six while the number of the salient poles of the stator is eight, the number of the salient poles of the rotor is eight while the number of the salient poles of the stator is twelve, and so forth.

[0004] When current is supplied to a pair of opposing winding coils (plural pairs of winding coils as the case may be) of the stator, magnetic fluxes directed from the salient poles of the stator to the salient poles of the rotor are generated to attract the salient poles of the rotor to the salient poles of the stator, so that a torque is generated. At this time, when one salient pole of the rotor is positioned so as to face to one salient pole of the stator, positions of remaining salient poles of the rotor are displaced mutually with remaining salient poles of the stator. Therefore, if the current is supplied to the winding coils by selecting the displaced salient poles of the stator sequentially, the salient poles of the rotor are attracted successively to them. Thus, the rotor can be rotated around the shaft.

[0005] Also, such SR motor can function as a generator. FIGS.1A and 1B are circuit diagrams showing a driving circuit in the prior art when an SR motor is used as a generator-motor. This driving circuit is provided to a plurality of windings constituting the same phase (winding sets) of the winding coils, that are fitted on the salient poles of the stator, respectively. For example, in the case of the three-phase motor in which the number of the salient poles of the stator is six and the number of the salient poles of the rotor is four, each phase (U phase, V phase, W phase) is composed of a pair of mutually opposing winding coils. These pairs of winding coils are connected in series to constitute the winding sets respectively, and then the driving circuit is provided to these winding sets respectively. In this disclosure, assume that the winding coil or the winding signifies not only a single winding coil but also a plurality of winding coils constituting the same phase (winding set).

[0006] As shown in FIGS.1A and 1B, a start terminal T1 of a winding coil C is connected to a power supply E via a power device such as a switching device (power transistor) SW1 and also connected to ground via the diode D1. An end terminal T2 of the winding coil C is connected to the power supply E via a diode D2 and also connected to ground via a power device such as a switching device SW2.

[0007] FIGS.2A to 2C are views showing control contents of operations of the switching devices SW1 and SW2, wherein FIG.2A shows a relationship between rotation angle of a rotor (abscissa) and inductance L (ordinate), FIG.2B shows a relationship between the rotation angle of the rotor (abscissa) and winding voltage (ordinate), and FIG.2C shows a relationship between the rotation angle of the rotor (abscissa) and winding current (ordinate).

[0008] When the rotation angle of the rotor becomes a predetermined angle (θ on) during a period in which the inductance L is decreasing, the voltage is applied to the winding coil C by turning ON the switching devices SW1 and SW2 simultaneously. At this time, as shown in FIG.1A, a current flows through a route consisting of the switching device SW1, the winding coil C, and the switching device SW2, and thus energy is supplied from the power supply E to generate the torque.

[0009] Then, when the rotation angle of the rotor becomes another predetermined angle (θ off) during the period in which the inductance L is still decreasing, the switching devices SW1 and SW2 are turned OFF simultaneously. At this time, as shown in FIG.1B, a current flows through a route consisting of the diode D1, the winding coil C, the diode D2 due to an electromotive force caused in the winding coil C to return the energy to the power supply E. Regenerative energy can be increased larger than supply energy by controlling the operations of the switching devices SW1 and SW2 in this manner, whereby the SR motor can be operated as the generator.

[0010] However, according to the controlling method in the prior art, a large current is caused to flow because the electromotive force is small, particularly in the low rotational range. As a result, there is such a problem that, since a power device having a large current capacity must be employed as the power device containing the switching device, cost is increased and the size of the device becomes large. Also, there is such another problem that copper loss of the winding is increased and thus the operation of the SR motor becomes ineffective. In addition, there is such still another problem that torque ripple and flutter is also increased correspondingly, since current extremely increases.

[0011] The present invention has been made in light of the above problems in the prior art, and it is an object of the present invention to provide an SR motor controlling method and an SR motor, which are capable of achieving highly effectively the reduction in cost and the improvement in performance.

[0012] According to an aspect of the present invention, there is provided a method of controlling an SR motor which includes a stator having a plurality of salient poles, windings wound around the plurality of salient poles and generating

magnetic fields in the plurality of salient poles, and a rotor having another plurality of salient poles (a number of the salient poles of the rotor being determined depending upon a number of the salient poles of the stator), the method comprising: executing, changeably as the rotor rotates, a supply mode for supplying power from a power supply to the windings, a reflux mode for setting both terminals of the windings to an identical potential, and a regenerative mode for recovering an electromotive force generated in the windings into the power supply.

[0013] In a preferred embodiment of the present invention, the supply mode, the reflux mode, and the regenerative mode are executed in that order.

[0014] In a preferred embodiment of the present invention, after the supply mode is executed, a repetitive mode during which the regenerative mode and the reflux mode are repeated alternatively is executed.

[0015] In a preferred embodiment of the present invention, after a first supply mode is executed, a first repetitive mode during which the regenerative mode and a second supply mode are repeated alternatively and a second repetitive mode during which the regenerative mode and the reflux mode are repeated alternatively are mixedly executed.

[0016] Another aspect of the present invention provides a method of controlling an SR motor which includes a stator having a plurality of salient poles, windings wound around the plurality of salient poles and generating magnetic fields in the plurality of salient poles, and a rotor having another plurality of salient poles (a number of the salient poles of the rotor being determined depending upon a number of the salient poles of the stator), the method comprising: executing a first supply mode for supplying power from a power supply to the windings; and then executing a repetitive mode during which the regenerative mode for recovering an electromotive force generated in the windings into the power supply and a second supply mode for supplying the power from the power supply to the windings are repeated alternatively.

[0017] Another aspect of the present invention provides an SR motor which includes a stator having a plurality of salient poles, windings wound around the plurality of salient poles and generating magnetic fields in the plurality of salient poles, and a rotor having another plurality of salient poles (a number of the salient poles of the rotor being determined depending upon a number of the salient poles of the stator), the SR motor comprising: a first switch configured to connect selectively start terminals of the windings to one polarity of a power supply; a second switch configured to connect selectively end terminals of the windings to other polarity of the power supply; a first diode interposed between the start terminals of the windings and the other polarity of the power supply, and configured to flow a current only in a direction toward the start terminals; a second diode interposed between the end terminals of the windings and one polarity of the power supply, and configured to flow the current only in a direction toward one polarity of the power supply; and a controller configured to control to execute, changeably as the rotor rotates, a supply mode in which the first switch and the second switch are connected simultaneously, a reflux mode in which one of the first switch and the second switch is connected and other of them is cut off, and a regenerative mode in which the first switch and the second switch are cut off simultaneously.

[0018] In a preferred embodiment of the present invention, the supply mode, the reflux mode, and the regenerative mode are executed in that order.

[0019] In a preferred embodiment of the present invention, after the supply mode is executed, a repetitive mode during which the regenerative mode and the reflux mode are repeated alternatively is executed.

[0020] In a preferred embodiment of the present invention, after a first supply mode is executed, a first repetitive mode during which the regenerative mode and a second supply mode are repeated alternatively and a second repetitive mode during which the regenerative mode and the reflux mode are repeated alternatively are mixedly executed.

[0021] Another aspect of the present invention, provides an SR motor which includes a stator having a plurality of salient poles, windings wound around the plurality of salient poles and generating magnetic fields in the plurality of salient poles, and a rotor having another plurality of salient poles (a number of the salient poles of the rotor being determined depending upon a number of the salient poles of the stator), the SR motor comprising: a first switch configured to connect selectively start terminals of the windings to one polarity of a power supply; a second switch configured to connect selectively end terminals of the windings to other polarity of the power supply; a first diode interposed between the start terminals of the windings and the other polarity of the power supply, and configured to flow a current only in a direction toward the start terminals; a second diode interposed between the end terminals of the windings and one polarity of the power supply, and configured to flow the current only in a direction toward one polarity of the power supply; and a controller configured to control to execute a first supply mode in which the first switch and the second switch are connected simultaneously, and then execute a repetitive mode in which the first switch and the second switch are cut off simultaneously and a second supply mode in which the first switch and the second switch are connected simultaneously.

[0022] The nature, principle, and utility of the invention will become more apparent from the following detailed description when read in conjunction with the accompanying drawings.

[0023] In the accompanying drawings:

FIGS.1A and 1B are circuit diagrams showing a configuration of an SR motor driving circuit in the prior art, wherein

FIG.1A shows a supply mode and FIG.1B shows a regenerative mode;

FIGS.2A to 2C are views showing execution timings of respective modes of the SR motor in the prior art, wherein FIG.2A shows a relationship between rotation angle of a rotor and inductance, FIG.2B shows a relationship between the rotation angle of the rotor and winding voltage, and FIG.2C shows a relationship between the rotation angle of the rotor and winding current;

FIGS.3A to 3D are graphs showing simulation results of the SR motor in the prior art, wherein FIG.3A shows a relationship between the rotation angle of the rotor and the inductance, FIG.3B shows a relationship between the rotation angle of the rotor and the winding voltage, FIG.3C shows a relationship between the rotation angle of the rotor and the winding current, and FIG.3D shows a relationship between the rotation angle of the rotor and torque;

FIG.4 is a plan view showing a configuration of an SR motor according to a first embodiment of the present invention;

FIGS.5A to 5C are circuit diagrams showing a configuration of an SR motor driving circuit according to the first embodiment of the present invention, wherein FIG.5A shows a supply mode, FIG.5B shows a regenerative mode, and FIG.5C shows a reflux mode;

FIGS.6A to 6D are views showing execution timings of respective modes, wherein FIG.6A shows a relationship between the rotation angle of the rotor (abscissa) and the inductance (ordinate), FIG.6B shows a relationship between the rotation angle of the rotor (abscissa) and an operation (on, off) of the switching device SW1 (ordinate), FIG.6C shows a relationship between the rotation angle of the rotor (abscissa) and an operation (on, off) of the switching device SW2 (ordinate), and FIG.6D shows relationship between the rotation angle of rotor (abscissa) and the winding current;

FIGS.7A to 7C are views showing execution timings of respective modes of the SR motor driving circuit according to the second embodiment of the present invention, wherein FIG.7A shows a relationship between the rotation angle of the rotor and the inductance, FIG.7B shows a relationship between the rotation angle of the rotor and the winding voltage, and FIG.7C shows a relationship between the rotation angle of the rotor and the winding current;

FIGS.8A to 8D are graphs showing simulation results of the SR motor driving circuit according to the second embodiment of the present invention, wherein FIG.8A shows a relationship between the rotation angle of the rotor and the inductance, FIG.8B shows a relationship between the rotation angle of the rotor and the winding voltage, FIG.8C shows a relationship between the rotation angle of the rotor and the winding current, and FIG.8D shows a relationship between the rotation angle of the rotor and the torque;

FIG.9 is a view showing an inductance used to calculate a current amplitude in the SR motor driving circuit according to the second embodiment of the present invention;

FIG.10 is a view showing an inductance used to calculate a current amplitude in an SR motor driving circuit according to a third embodiment of the present invention;

FIGS.11A to 11C are views showing execution timings of respective modes of the SR motor driving circuit according to the third embodiment of the present invention, wherein FIG.11A shows a relationship between the rotation angle of the rotor and the inductance, FIG.11B shows a relationship between the rotation angle of the rotor and the winding voltage, and FIG.11C shows a relationship between the rotation angle of the rotor and the winding current;

FIGS.12A to 12C are views showing execution timings of respective modes of an SR motor driving circuit according to a fourth embodiment of the present invention, wherein FIG.12A shows a relationship between the rotation angle of the rotor and the inductance, FIG.12B shows a relationship between the rotation angle of the rotor and the winding voltage, and FIG.12C shows a relationship between the rotation angle of the rotor and the winding current;

FIGS.13A to 13C are views showing execution timings in respective modes of an SR motor driving circuit according to a fifth embodiment of the present invention, wherein FIG.13A shows a relationship between a rotation angle of the rotor and the inductance, FIG.13B shows a relationship between the rotation angle of the rotor and the winding voltage, and FIG.13C shows a relationship between the rotation angle of the rotor and the winding current;

FIGS.14A and 14B are views showing start timings of the initial supply mode according to a sixth embodiment of the present invention, wherein FIG.14A shows a relationship between a rotation angle of the rotor (abscissa) and the inductance L (ordinate), and FIG.14B shows a relationship between the rotation angle of the rotor (abscissa) and the winding current (ordinate);

FIG.15 is a graph showing a relationship between start timings in the supply mode and an amount of power generation if a first current value is set variously in the sixth embodiment of the present invention;

FIGS.16A and 16B are views showing start timings of the last regenerative mode in the sixth embodiment of the present invention, wherein FIG.16A shows a relationship between the rotation angle of the rotor (abscissa) and the inductance L (ordinate), and FIG.16B shows a relationship between the rotation angle of the rotor (abscissa) and the winding current (ordinate);

FIG.17 is a view showing a waveform of the SR motor having a different inductance waveform in the sixth embodiment of the present invention;

FIG.18 is a circuit diagram applied to the case where PWM current control is carried out in the second embodiment

of the present invention; and

FIGS.19A to 19C are views showing the case where PWM current control is carried out in the third embodiment of the present invention, wherein FIG.19A shows a relationship between the rotation angle of the rotor and the inductance, FIG.19B shows a relationship between the rotation angle of the rotor and the winding voltage, and FIG.19C shows a relationship between the rotation angle of the rotor and the winding current.

[0024] Embodiments of the present invention will be explained in detail with reference to the accompanying drawings hereinafter.

First Embodiment

[0025] A first embodiment of the present invention will be explained with reference to figures hereunder. FIG.4 is a plan view showing a configuration of an SR motor (switched reluctance motor) according to a first embodiment of the present invention. FIGS.5A to 5C are circuit diagrams showing a configuration of an SR motor driving circuit according to the first embodiment of the present invention, wherein FIG.5A shows a supply mode, FIG.5B shows a regenerative mode, and FIG.5C shows a reflux mode. The SR motor 1 is a three-phase motor in which the number of salient poles of the stator is set to six and the number of salient poles of the rotor is set to four. For example, the SR motor 1 is a generator-motor that can also function as a generator directly coupled with an engine of a vehicle.

[0026] First, FIG.4 is referred to. The SR motor 1 is constructed to comprise a rotor 2, a stator 3, a motor housing (not shown) for containing them, etc.

[0027] The rotor 2 is constructed by inserting an output shaft 5 into a through hole formed on a center of a rotor core 4, that has a plurality of (four in this embodiment) salient poles 2a, and then fixing them integrally. The output shaft 5 is supported to the motor housing via bearings. In this embodiment, the rotor core 4 is constructed by laminating integrally a plurality of magnetic steel plates that are stamped out by a punching machine. The number of rotations (rpm) of the output shaft 5 per unit time is counted by a number-of-rotations detecting unit (not shown). The angle of rotation of the output shaft 5 is constantly detected by an angle-of-rotation detecting unit.

[0028] The stator 3 is constructed to include a stator core 6 and a plurality of winding coils 7. The stator core 6 is constructed by providing integrally a plurality of (six in this embodiment) salient poles 3a that protrude toward the inside of an almost cylindrical yoke portion in the radial direction. In this embodiment, the stator core 6 is constructed by laminating integrally a plurality of magnetic steel plates that are stamped out by a punching machine. The stator 3 is fixed to the inside of the motor housing.

[0029] The winding coils 7 are fitted onto six salient poles of the stator core 6 respectively. A pair of opposing winding coils 7 are connected in series to constitute a winding set, and respective phases (U phase, V phase, W phase) are constructed by these three winding sets. The winding coils 7 are wound directly onto the salient poles 3a of the stator core 6, otherwise are wound onto bobbins formed of resin respectively and then fitted onto the salient poles 3a. The rotor 2 is inserted into the stator 3 and then positioned coaxially to have a predetermined gap between the salient poles 2a of the rotor 2 and the salient poles 3a of the stator 3.

[0030] When the current is supplied to the winding coils 7, the magnetic fluxes directed from the salient poles 3a of the stator 3 to the salient poles 2a of the rotor 2 are generated to attract the neighboring salient poles 2a of the rotor 2 to the salient poles 3a of the stator 3, whereby the torque is generated. At this time, when one salient pole 2a of the rotor 2 is positioned to face to one salient pole 3a of the stator 3, positions of remaining salient poles 2a of the rotor 2 are displaced mutually with remaining salient poles 3a of the stator 3. Therefore, if the current is supplied to the winding coils by selecting the displaced salient poles 3a of the stator 3 sequentially, i.e., if the current is supplied sequentially to the winding coil constituting the U phase, the winding coil constituting the V phase, and the winding coil constituting the W phase, the salient poles 2a of the rotor 2 are attracted successively to the salient poles 3a of the stator 3. Thus, the rotor 2 can be rotated around the shaft.

[0031] The SR motor driving circuit is constructed as shown in FIGS.5A to 5C. In the following description, the driving circuit of the winding set constituting the U phase will be explained. In this case, the driving circuits of the winding sets constituting the V, W phases have the similar configuration.

[0032] A start terminal T1 of the winding set C, that consists of a pair of winding coils 7 constituting the U phase, is connected to the power supply E (e.g., (+) pole of a battery for a vehicle) via a power device such as a switching device (power transistor) SW1, and also connected to ground ((-) pole of the battery) via a diode D1. An end terminal T2 of the winding set C is connected to the power supply E via a diode D2, and also connected to ground via a similar power device such as a switching device SW2.

[0033] A current sensor 11 is provided to the end terminal T2 of the winding set C. Based on a detected angle of the angle-of rotations detecting unit and a detected current of the current sensor, etc., operations of the switching devices SW1, SW2 are controlled by a control device 12 respectively.

[0034] The control device 12 of this embodiment executes appropriately three control modes, i.e., a supply mode,

a regenerative mode, and a reflux mode. The supply mode is a mode which supplies power to the winding set C, and is a mode that turns ON the switching devices SW1 and SW2 simultaneously, as shown in FIG.5A. According to the supply mode, the current flows through a route consisting of the switching device SW1, the winding set C, and the switching device SW2, and thus the energy is supplied from the power supply E to generate the torque during this period.

[0035] The regenerative mode is a mode in which the electromotive force generated in the winding set C is withdrawn. As shown in FIG.5B, the switching devices SW1 and SW2 are turned OFF simultaneously in the regenerative mode. According to the regenerative mode, the current flows through a route consisting of the diode D1, the winding set C, and the diode D2, and thus the energy is returned to the power supply E in this mode. If the regenerative energy is increased larger than the supply energy by setting appropriately ON/OFF timings of the switching devices SW1 and SW2, i.e., by executing appropriately the supply mode and the regenerative mode, this SR motor can be operated as the generator.

[0036] The reflux mode is a mode which is newly provided by the present invention and in which both terminals of the winding set C are set to the same potential. That is, as shown in FIG.5C, the switching device SW2 is set to its ON and the switching device SW1 is set to its OFF in this mode. In FIG.5C, according to the reflux mode, the current flows through a route consisting of the diode D1, the winding set C, and the switching device SW2, and thus there is no revenue and expenditure of the energy in this mode because the current is returned to ground. In this case, the reflux mode may be achieved by setting the switching device SW1 to its ON and setting the switching device SW2 to its OFF.

[0037] FIGS.6A to 6D are views showing execution timings of respective modes, wherein FIG.6A shows a relationship between the rotation angle of the rotor (abscissa) and the inductance (ordinate), FIG.6B shows a relationship between the rotation angle of the rotor (abscissa) and an operation (on, off) of the switching device SW1 (ordinate), FIG.6C shows a relationship between the rotation angle of the rotor (abscissa) and an operation (on, off) of the switching device SW2 (ordinate), and FIG.6D shows relationship between the rotation angle of the rotor (abscissa) and the winding current.

[0038] As shown in these figures, according to the first embodiment, the supply mode is started by turning ON the switching devices SW1 and SW2 simultaneously when the rotor is positioned at a predetermined rotation angle θ_1 in the rising latter half period of the inductance L. Thus, the current flowing through the winding set C is increased. Then, the reflux mode replaces the supply mode by turning OFF the switching device SW1 while keeping the switching device SW2 in its ON state as it is when the inductance L is turned to the reduction (rotation angle θ_0 of the rotor) or when the rotor is positioned at a predetermined rotation angle θ_2 at the beginnings of the falling period of the inductance L.

[0039] Next, the regenerative mode is started by turning OFF the switching device SW2 while keeping the switching device SW1 in its OFF state as it is when the rotor is positioned at a predetermined rotation angle θ_3 (at a point of time prior to a point of time when the inductance L is turned from the falling to the plateau). The regenerative mode continues until the current becomes zero.

[0040] The more detail explanations will be provided hereinunder assuming that the rotor is driven at a constant rotation rate by an external control. If the switching devices SW1 and SW2 are simultaneously turned ON when the rotor is positioned at a predetermined rotation angle θ_1 and no current is flowing through the winding coils, the current starts to rise. The current is represented by the following equation.

$$\begin{aligned} V &= Ri + L(di/dt) + i\,\omega(dL/d\,\theta) \\ &= (R + \omega(dL/d\,\theta))i + L(di/dt) \end{aligned} \tag{1}$$

where the winding inter-terminal voltage is V, the winding resistance is R, the winding current is i, the rate of change of the current is (di/dt), the number of rotations of the rotor per unit time is ω, the winding inductance is L and the rate of change of the inductance is ($dL/d\,\theta$).

[0041] Since it is generally known that the inductance L relative to the rotation angle of an SR motor can be approximated to linear lines of chopping wave as shown in FIG.6A, $\omega(dL/d\,\theta)$ shows three processes: a process in which the inductance linearly rises, a process in which the inductance linearly falls, and a process in which the inductance is almost constant, in the condition that the number of rotations of the rotor per unit time is constant (except $\omega = 0$).

[0042] As described before, if the switching devices SW1 and SW2 simultaneously turns ON at a rotation angle of $\theta = \theta_1$ ($\theta 1 < \theta 0$) of the rotor, ($dL/d\,\theta$) in the equation (1) has a positive value in an early period of excitation, which means apparent increasing of resistance of the circuit thereof; therefore the current i gently rises. Then, when the rotation angle becomes $\theta > \theta 0$ after the corresponding rotation of the rotor, ($dL/d\,\theta$) has a negative value conversely, which means apparent decreasing of resistance of the circuit thereof, therefore the current i prominently rises. Particularly, if ω has a value which makes $R + \omega(dL/d\,\theta)$ negative, which means that apparently the resistance value is negative and thus increasing of current causes increasing of the value of L(di/dt), therefore the current continues to rise.

[0043] Thereafter, if the switching device SW1 is turned OFF when the rotation angle θ becomes θ 2, the current returns as shown in FIG.6C.

[0044] In the reflux mode, the winding terminal voltage is 0 [V]. Therefore, 0 is substituted to V in the equation (1) and thus the following equation (2) is obtained.

$$L(di/dt) = -(R + \omega(dL/d\,\theta))i \tag{2}$$

[0045] Considering into account that all of the inductance L, the winding resistance R, the number of rotations of the rotor per unit time is ω, and the current i is positive and only (dL/d θ) is negative, the current i increases while returning, as shown in FIG.6D, only in the condition that ω satisfies $(R + \omega(dL/d\,\theta)) < 0$. This means that the winding converts the energy required for the rotations from an external driving source which drives the rotor at a constant rotation rate, into electric energy to store it therein.

[0046] Thereafter, if the switching device SW2 that has been ON is turned OFF when the rotation angle θ becomes θ 3, the current flowing through the winding is regenerated into a power supply.

[0047] If θ 3 is set to be larger than the angle θ d at which the inductance L becomes the constant value L0, the current which has increased turns to decreasing because the region where (dL/d θ) in the equation (2) is 0 is included. This makes generation amount of electric energy decrease, which should be avoided.

[0048] As described above, according to this embodiment, the reflux mode lies between the supply mode and the regenerative mode. Therefore, even the rotation number per unit time of the rotor is low, prominent increase of the winding current is prevented. For this reason, as constituent parts of the driving circuit such as the power device containing the switching devices SW1, SW2, the diodes D1, D2, and others, parts having a small current capacity can be employed. As a result, since normally such parts are inexpensive rather than the parts having the large current capacity, reduction in cost and size of the SR motor can be achieved.

[0049] Also, if the reflux mode is executed after the execution of the supply mode, rotation energy of the rotor is accumulated in the winding as electric energy, and the current flowing through the winding gently rises without consuming electric power as shown in FIG.6D. For this reason, in the regenerative mode after that, the electric energy the amount thereof is more by the rising is obtained.

[0050] Particularly, in this embodiment, the supply mode starts before the peak (θ 0) of the inductance of the winding during the rising period of the inductance along with the rotation of the rotor, and the reflux mode starts at the beginnings of the falling period of the inductance of the winding along with the rotation of the rotor. Therefore almost all the range in which the inductance falls as the rotor rotates, and thus electric energy can be inherently generated, can be utilized to increase the generation amount of electric energy. Further, the regenerative mode starts before the end of the falling period of the inductance of winding along with the rotation of the rotor so that the reduction of the generation amount of electric energy can be avoided.

[0051] In this embodiment, the rotation angle θ of the rotor is always detected, and the supply mode starts when the rotation angle θ of the rotor reaches the predetermined angle θ 1, the reflux mode replaces the supply mode when the rotation angle θ reaches the predetermined angle θ 2, and the regenerative mode replaces the reflux mode when the rotation angle θ reaches the predetermined angle θ 3. Another criterion can be, however, applied such that the reflux mode replaces the supply mode when winding current detected by a current detector reaches a predetermined first current value I2, and the regenerative mode replaces the reflux mode when the winding current reaches a predetermined second current I3. The second current value I3 may be set to be larger than the first current value I2.

<u>Second Embodiment</u>

[0052] A second embodiment of the present invention will be explained with reference to figures hereunder. The configurations of the SR motor and the SR motor driving circuit according to the second embodiment of the present invention are same as those of the first embodiment as shown in FIG.4 and FIGS.5A to 5C.

[0053] FIGS.7A to 7C are views showing execution timings of respective modes, wherein FIG.7A shows a relationship between the rotation angle of the rotor (abscissa) and the inductance (ordinate), FIG.7B shows a relationship between the rotation angle of the rotor (abscissa) and the winding voltage (ordinate), and FIG.7C shows a relationship between the rotation angle of the rotor (abscissa) and the winding current (ordinate).

[0054] As shown in FIGS.7A to 7C, in the second embodiment, the supply mode is started by turning ON the switching devices SW1 and SW2 simultaneously when the rotor reaches a predetermined rotation angle θ_{on} at the end of the rising period of the inductance L. Thus, the current flowing through the winding set C is increased. Then, the regenerative mode is executed by turning OFF the switching devices SW1 and SW2 simultaneously when the inductance L is turned to the reduction or when the winding current detected by the above current sensor (detected current) reaches a predetermined upper limit value i_m at a point of time in the succeeding falling period. Thus, the winding current is reduced. Then, the reflux mode is executed by turning ON the switching device SW2 while keeping the switching device SW1 in its OFF state as it is when the detected current detected by the above current sensor comes up to a predetermined lower limit value. Thus, the winding current is increased once again.

[0055] In the following, when the detected current reaches the predetermined upper limit value and the predetermined lower limit value respectively, the reflux mode and the regenerative mode are alternatively repeated. Then, when the rotor is positioned at a predetermined rotation angle θ_{off} (at a point of time prior to a point of time when the inductance L is turned from the falling to the plateau), repetitive control of the regenerative mode and the reflux mode is completed. After this, the regenerative mode continues until the current becomes zero.

[0056] According to this embodiment, since the regenerative mode and the reflux mode are alternatively repeated such that the winding current is held in the range between the predetermined upper limit value and the predetermined lower limit value after the supply mode is executed, the prominent increase of the winding current can be prevented even if the number of rotations of the rotor is in the low rotation range, and the winding current can be held below the predetermined value. Therefore, as constituent parts of the driving circuit such as the power device containing the switching devices SW1, SW2, the diodes D1, D2, and others, parts having a small current capacity can be employed. As a result, since normally such parts are inexpensive rather than the parts having the large current capacity, reduction in cost of the SR motor can be achieved.

[0057] In addition, the winding current is reduced by the execution of the regenerative mode, but the winding current is increased (recovered) by the execution of the reflux mode. Therefore, the winding current can be held within the predetermined range (range between the upper limit value and the lower limit value), and thus the output is not reduced or the output can be increased higher even if the current peak is suppressed low.

[0058] In addition, in the above embodiment, since the supply mode is executed in the rising latter half period of the winding inductance L and also the regenerative mode and the reflux mode are executed successively in the falling period of the winding inductance L, efficiency of power generation becomes high.

[0059] Here, the circuit equation in the supply mode is given by

$$L(di/dt) = V - Ri - (dL/d\theta)i\,\omega \tag{3}$$

where the winding inter-terminal voltage is V, the winding resistance is R, the winding current is i, the rate of change of the current is (di/dt), the number of rotations of the rotor per unit time is ω, the winding inductance is L, and the rate of change of the inductance is (dL/d θ).

[0060] In the reflux mode, since the voltage applied across the winding is 0 [V], the circuit equation is given by

$$L(di/dt) = -(R + (dL/d\theta)\omega)i$$

by substituting V = 0 into Eq.(3). At this time, the current is increased if

$$-(R + (dL/d\theta)\omega)i > 0 \tag{4}$$

Since i has only a positive value structurally and the reflux mode is executed in the falling period of the winding inductance, (dL/d θ) becomes negative.

[0061] Accordingly, the inequality in Eq.(4) is given by

$$\omega > -R/(dL/d\theta) \tag{5}$$

This inequality in Eq.(5) yields the lowest number-of-rotations condition to increase the current in the reflux mode.

[0062] If quite normal values $R = 0.2\ \Omega$ and $(dL/d\theta) = -(10\ mH-1\ mH)/(30\ degrees)$, for the purpose of reference, are substituted into the inequality in Eq.(5), $\omega > 55$ rpm is given. Thus, the SR motor can be employed from the very low rotation range. Then, in the regenerative mode, the voltage applied between both terminals of the winding denotes the backward bias. Therefore, substituting $V = -E$ (E is the power supply voltage) into Eq.(3) yields

$$L(di/dt) = -E - (R+(dL/d\theta)\omega)i$$

Then, the current can be reduced if

$$-E - (R + (dL/d\theta)\omega)i < 0 \tag{6}$$

In other words, if the left side of the inequality in Eq.(6) is positive, the current is continued to increase. Thus, it is impossible to control the SR motor.

[0063] Now, if it is assumed that the condition defined by Eq.(4) can be satisfied, the inequality

$$i < -E/(R + (dL/d\theta)\omega) \tag{7}$$

can be given. This Eq.(7) yields the maximum current condition to reduce the current in the regenerative mode. If quite normal values $E = 100$ V and $\omega = 1000$ rpm, for the purpose of reference, are substituted into Eq.(7), the winding current $i < 58$ A can be given.

[0064] FIGS.8A to 8D are graphs showing simulation results obtained when the configuration according to the second embodiment is employed. FIGS.3A to 3D are graphs showing simulation results obtained when the configuration in the prior art is employed in contrast to the above. FIGS.8A and 3A show a relationship between the rotation angle of the rotor (abscissa) and the inductance (ordinate), FIGS.8B and 3B show a relationship between the rotation angle of the rotor (abscissa) and the winding voltage (ordinate), FIGS.8C and 3C show a relationship between the rotation angle of the rotor (abscissa) and the winding current (ordinate), and FIGS.8D and 3D show a relationship between the rotation angle of the rotor (abscissa) and the torque (ordinate).

[0065] These simulation results are obtained at the time of 700 rpm/1 kW output. In order to attain the same output, the current peak can be considerably reduced like 300 A rather than 540 A in the prior art. Accordingly, it can be understood that the peak of the torque is reduced and becomes uniform and thus torque ripple can be reduced.

[0066] Next, the upper limit value i_m and the lower limit value that are current values used to control mode switching timing during the repeating period of the regenerative mode and the reflux mode will be explained hereunder. In this disclosure, a value corresponding to a difference between the upper limit value and the lower limit value is referred to as a current amplitude Δi.

[0067] It is possible to say that the smaller current amplitude Δi is advantageous to the SR motor. The reason for this can be given as follows. That is, the above repetitive control is finished at the point of time when the rotation angle of the rotor reaches θ_{off} after the regenerative mode and the reflux mode have been repeated, and then the regenerative mode is executed until the current is reduced to zero. In this case, it is a matter of course that the range of the current value taken at the instant of θ_{off} is small as the current amplitude Δi becomes small, and therefore variation in a power generation amount in the regenerative mode can be reduced after the rotor has passed through θ_{off}. In addition, if the current amplitude Δi becomes smaller, the torque ripple can be reduced much more and also the average current can be increased, and therefore the power generation amount can be increased correspondingly.

[0068] On the contrary, there is a problem that, if the current amplitude Δi is made small, switching frequencies of the switching devices SW1, SW2 become higher. Normally, the maximum value of the switching frequency that is allowable in specifications of the switching device is decided. Thus, if the switching device is operated at the frequency that exceeds the maximum value, the proper operation of the switching device cannot be assured. In the worst case, destruction of the switching device may be brought about.

[0069] Accordingly, ideally it is preferable that the current change period in the repetitive period of the regenerative mode and the reflux mode, i.e., a time Δt that correspond to a sum of respective execution times of the regenerative mode and the succeeding reflux mode, should be set to coincide to the minimum switching period (reciprocal of the maximum switching frequency) $\Delta t0$ of the switching devices SW1, SW2.

[0070] A relationship between the current amplitude Δi and the current change period Δt in the repeating period can be derived as follows.

[0071] That is, the circuit equation of the SR motor is given by

$$di/dt = \{V - [R + \omega(dL/d\theta)]i\}/L(\theta) \tag{8}$$

where the winding inter-terminal voltage is V, the winding resistance is R, the winding current is i, the rate of change of the current is (di/dt), the number of rotations of the rotor per unit time is ω, the winding inductance of the rotor at the rotation angle θ is $L(\theta)$, and the rate of change of the inductance is $(dL/d\theta)$.

[0072] In Eq.(8), assume that $i=i_m$ (constant) because the current amplitude Δi is sufficiently small and that $L(\theta) = L_m$ (constant) because the low speed rotation is discussed herein. Thus, the rate of change (di/dt) of the current to the time becomes constant if the number of rotations ω and the voltage V are decided. In other words, in the regenerative mode (1 is appended as the index), substituting $V = -E$ (E is the power supply voltage) into Eq.(8) yields

$$di_1/dt_1 = \{-E - [R + \omega(dL/d\theta)]i_m\}/L_m \tag{9}$$

[0073] In the reflux mode (2 is appended as the index), substituting $V = 0$ into Eq.(8) yields

$$di_2/dt_2 = -[R + \omega(dL/d\theta)]i_m/L_m \tag{10}$$

Since the current amplitude Δi at this time is equal in respective modes,

$$di_1 = -\Delta i,\ di_2 = \Delta i \tag{11}$$

are given. Also, the current change period (time period corresponding to a sum of execution times of the regenerative mode and the following reflux mode) Δt in the repeating period is given by

$$\Delta t = dt_1 + dt_2 \tag{12}$$

Therefore,

$$\Delta t = \Delta i \cdot EL_m/(\alpha(E - \alpha)) \tag{13}$$

can be derived based on Eqs.(9) to (12), where

$$\alpha = -(R + \omega(dL/d\theta))i_m$$

[0074] If the current amplitude Δi which can provide Δt shown in Eq.(13) to satisfy

$$\Delta t \geqq \Delta t_o \tag{14}$$

with respect to the minimum switching period $\Delta t0$ (reciprocal of the maximum switching frequency) of the switching devices SW1, SW2 is calculated and then the upper limit value and the lower limit value of the current to control the repeating operation are set based on this current amplitude Δi, the switching operations of the switching devices SW1, SW2 do not exceed the limits and thus the problems of the breakdown, etc. are not caused at all. In this case, it is preferable that Δi should be set to satisfy the equality sign in Eq.(14). This is because the breakdown of the switching devices SW1, SW2 is never caused, variation in the power generation amount can be reduced as small as possible, and the power generation amount can be increased as much as possible. Then, decision of the inductance (instantaneous inductance) L_m in Eq.(13) will be explained hereunder. As shown in FIGS.7A to 7C, if the current amplitude Δi in the repeating period of the regenerative mode and the reflux mode is set constant as described above, the switching frequency is increased with the lapse of time in the period when the winding inductance L is reduced as the rotor rotates. That is, the switching frequency reaches a maximum in the last one period (see the A portion in FIG.7C) of the current change in the repeating period. This is because the inductance L can be reduced to accelerate the current response. Accordingly, if the current amplitude Δi is set such that the switching frequency in the last one period does not exceed the maximum switching frequency of the switching devices SW1, SW2, the actual switching frequency of the switching devices SW1, SW2 never exceeds the maximum switching frequency over the entire period of the repeating period.

[0075] In this case, the current amplitude is calculated by substituting the minimum inductance L_o into the instantaneous inductance L_m. The grounds for this calculation is that, since the actual inductance of the winding never becomes smaller than the minimum inductance L_o, the calculation using the minimum inductance L_o ensures that the actual switching frequency of the switching devices SW1, SW2 never exceed the maximum switching frequency over the entire period of the repeating period.

[0076] The repeating period of the regenerative mode and the reflux mode terminates at the predetermined rotation angle θ_{off} of the rotor. The angle θ_{off}, however, may be set to be an angle corresponding to a point of time during the falling period of inductance L of the winding, in other words, an angle before the inductance L reaches the minimum inductance L_o. In this case, the current amplitude Δi obtained by using the minimum inductance L_o can not sufficiently bring out the switching ability of the switching devices SW1, SW2.

[0077] In this case, if the inductance L_2 corresponding to θ_{off} is substituted into the inductance L_m in Eq.(13) to calculate the current amplitude, the actual switching frequency in the last one period of current change in the repeating period becomes closer to the maximum switching frequency of the switching devices SW1, SW2, and thus power generation amount becomes larger, compared with the case in which the minimum inductance L_o is used. It is noted that, in the case where the inductance L_2 corresponding to θ_{off} is used in the control as described above, it is necessary to store in advance the relation between θ_{off} in the range of use and the inductance into a memory device in a controller such as a microcomputer and calculate the current amplitude Δi according to Eq.(13) every time, because θ_{off} varies in a certain range depending upon various conditions.

[0078] Further, even in the case where the inductance L_2 corresponding to θ_{off} is used to obtain the current amplitude Δi, the period $\Delta t(dt_1+dt_2)$ calculated according to Eq.(13) is slightly larger than the minimum switching period Δt_0, since the inductance L_2 corresponding to θ_{off} is an inductance after the last one period in the repeating period terminates. Therefore, if the current amplitude Δi should be reduced much more, such current amplitude Δi can be calculated by substituting an inductance (inductance prior to θ_{off} by the half period) L_3, which is obtained when the rotation angle of the rotor is $\theta_{off} -(\Delta t/2) \cdot \omega$, into the inductance L_m in Eq.(13). As shown in FIG.9, this inductance L_3 is an inductance at an almost intermediate point of time in the last one period of the repeating period, and can be assumed

as an average inductance in the last one period. Therefore, it can be estimated that the period Δ t at this time becomes very close to the minimum switching period Δ t0, so that the power generation amount can be increased up to the maximum.

Third Embodiment

[0079] A third embodiment of the present invention will be explained with reference to the drawings hereunder. In the above second embodiment, the upper limit value i_m of the current and the current amplitude Δ i to control the repeating operation of the regenerative mode and the reflux mode are set constant in the overall repeating period of the regenerative mode and the reflux mode. In contrast, in the third embodiment, the current amplitude Δ i is changed positively with the lapse of time (rotation angle of the rotor). Since an overall configuration of the SR motor and a configuration of the driving circuit are similar to those in the above first embodiment, their explanation will be omitted.

[0080] In the above second embodiment, the current amplitude Δ i is set such that the switching period Δ t of the current change in the last one period during the repeating period does not exceed the minimum switching period Δt_0 of the switching devices SW1, SW2. If the switching period is controlled to make the current amplitude Δ i constant, the actual switching period in the former half (see the B portion in FIG.7C) of the repeating period becomes longer than the minimum switching period and thus the switching capability of the switching devices SW1, SW2 is not fully utilized. Therefore, the current amplitude Δ i in this period is set smaller than the current amplitude Δ i in the last one period, it is possible to increase the power generation amount much more.

[0081] This event will be explained with reference to FIG.10 hereunder. First, if the supply mode is started by turning ON the switching devices SW1, SW2 simultaneously when the rotor is positioned at the rotation angle θ_{on} in the rising latter half period of the inductance, the current is increased to reach the predetermined upper limit value i_m of the current. Then, the rotation angle θ m of the rotor is detected at that time. Assume that an inductance (initial i_m arrival inductance) L_4 at a point of time of the angle θ m is stored and held previously in a memory device of a controller. Then, the current amplitude Δ i at this time (this value is referred to as Δi_1) is calculated by substituting the initial i_m arrival inductance L_4 into the inductance L_m in Eq.(13) in the second embodiment. The current amplitude Δ i at the time of θ_{off} (this value is referred to as Δi_2) has already been calculated by substituting the θ_{off} -time inductance L2 into Eq.(13).

[0082] Then, the rotation angle θ of the rotor is changed from θ m to θ_{off}, whereas the current amplitude Δ i is changed linearly from Δi_1 to Δi_2. Accordingly, as shown in FIGS.11A to 11C, not only the actual switching period Δ t becomes substantially constant in the overall repeating period of the regenerative mode and the reflux mode, but also such actual switching period Δ t can substantially coincide to the minimum switching period Δt_0, and thus it is possible to maximize the power generation amount without destroying the switching devices SW1, SW2. Further, the dispersion of the power generation amount and the current ripple can be curbed. Therefore, the load on the power supply and the auxiliary parts thereof (capacitor connected in parallel to the power supply) is reduced. Here, FIGS.11A to 11C are views showing execution timings of respective modes according to the second embodiment of the present invention, wherein FIG.11A shows a relationship between the rotation angle of the rotor (abscissa) and the inductance L (ordinate), FIG.11B shows a relationship between the rotation angle of the rotor (abscissa) and the winding applied voltage (ordinate), and FIG.11C shows a relationship between the rotation angle of the rotor (abscissa) and the winding current (ordinate).

[0083] Also, in order to render the switching period Δ t constant, there is a method employing PWM current control. According to the PWM current control, a difference between a current command value i_m and a current detection value is calculated, and then an ON duty and an OFF duty are generated by comparing this difference value with a chopping wave having a predetermined period. This PWM current control is illustrated in a circuit diagram shown in FIG.18. According to a configuration in FIG.18, if a compared value (comparator output) between the difference value and the chopping wave having the predetermined period is positive, the switching device SW2 is turned ON to execute the reflux mode whereas, if the comparator output is negative, the switching device SW2 is turned OFF to execute the regenerative mode. In this manner, according to the PWM current control, the regenerative mode and the reflux mode are repeated at the predetermined period. It is desired that this repeating period should be set as small as possible to reduce the current amplitude, and thus such repeating period can be decided in response to the minimum switching period of the switching devices SW1, SW2. FIG.19C shows the current waveform when the above PWM current control is applied, and gives the repetitive waveform of the regenerative mode and the reflux mode which has a constant frequency. In this case, a sawtooth waveform may be used in place of the chopping waveform. As described above, as a general-purpose PWM control circuit parts can be applied, a control circuit of an SR motor can be easily realized by using general-purpose parts, and also the production cost can be reduced.

[0084] As described above, if the PWM current control is applied, it is easy to make the switching period Δ t constant. In addition, it is easy to change the rate of the period of the regenerative mode to the period of the reflux mode in each switching period by changing the duty ratio, such as 6 to 4, 7 to 3, etc., while keeping switching period Δ t constant.

Fourth Embodiment

[0085] A fourth embodiment of the present invention will be explained with reference to the drawings hereunder. In the above second and third embodiments, after the supply mode has been executed, the regenerative mode and the reflux mode are executed repeatedly. In contrast, in this fourth embodiment, after the supply mode (first supply mode) has been executed, the regenerative mode and the supply mode (second supply mode) are executed repeatedly.
[0086] FIGS.12A to 12C are views showing execution timings of respective modes according to the fourth embodiment of the present invention, wherein FIG.12A shows a relationship between the rotation angle of the rotor (abscissa) and the inductance L (ordinate), FIG.12B shows a relationship between the rotation angle of the rotor (abscissa) and the winding applied voltage (ordinate), and FIG.12C shows a relationship between the rotation angle of the rotor (abscissa) and the winding current (ordinate).
[0087] As shown in FIGS.12A to 12C, in the fourth embodiment, the supply mode (first supply mode) is started by turning ON the switching devices SW1, SW2 at the same time when the rotor is positioned at the predetermined rotation angle θ_{on} in the rising latter half period of the inductance L. Accordingly, the current flowing through the winding is increased. Then, when the winding current (detected current) reaches the predetermined upper limit value i_m at a point of time when the inductance L is turned to fall or in the succeeding falling period, the regenerative mode is executed by turning OFF the switching devices SW1, SW2 simultaneously. Accordingly, the winding current is reduced. Then, when the current is reduced from the upper limit value by the predetermined current amplitude Δi to thus reach the predetermined lower limit value, the supply mode (second supply mode) is executed by turning ON the switching devices SW1, SW2 at the same time. Accordingly, the winding current is increased once again.
[0088] Similarly, when the detected current reaches the predetermined upper limit value and the predetermined lower limit value respectively, the regenerative mode and the supply mode are alternatively executed repetitively. Then, when the rotor is positioned at the predetermined rotation angle θ_{off} (at a point of time prior to a point of time when the inductance L is turned from the falling to the plateau), the repeating control of the regenerative mode and the supply mode is completed. Then, the regenerative mode is executed until the current is reduced to zero.
[0089] Like the above second embodiment, in the control method of repeating the regenerative mode and the supply mode, since the increase in the current in the reflux mode is gentle when the SR motor is used in the low rotational range, the execution time of the regenerative mode is shortened corresponding the gentle increase to thus reduce the power generation amount. In contrast, since the increase in the current in the supply mode is large rather than that in the reflux mode and thus the current reaches quickly the upper limit value, the execution time of the regenerative mode can be extended correspondingly to thus increase the power generation amount. Also, in the very low rotational range in which the number of rotations of the rotor is further low, the current is not increased by carrying out the reflux mode, as described above. However, in the fourth embodiment, since the supply mode is executed in place of the reflux mode, the SR motor can be employed in the very low rotational range not to cause the problem.
[0090] In the fourth embodiment, like the above second embodiment, the upper limit value and the current amplitude Δi that are the current values to control the mode switching timing are employed in the repeating period in which the regenerative mode and the supply mode are repeated. Thus, it is true that, as discussed in the above second embodiment, the smaller current amplitude Δi is advantageous to the SR motor. Therefore, since its control is almost similar, explanation will be omitted.
[0091] However, since the supply mode is executed instead of the reflux mode, the following Eq.(15) derived by modifying above Eq.(10) in connection with the current amplitude Δi must be applied. In other words, substituting $V = E$ in the supply mode into Eq.(8) yields

$$di_2/dt_2 = \{E - [R + \omega(dL/d\theta)]i_m\}/L_m \tag{15}$$

[0092] Accordingly,

$$\Delta t = \Delta i \cdot 2EL_m/(E^2 - \alpha^2) \tag{16}$$

is obtained based on Eqs.(9),(11),(12),(15), where $\alpha = -(R + \omega(dL/d\theta))i_m$.
[0093] The current amplitude Δi which can satisfy above Eq.(14) with respect to the minimum switching period (reciprocal of the maximum switching frequency) Δt_0 of the switching devices SW1, SW2 is calculated, and then the upper limit value and the lower limit value of the current to control the repeating operation are set based on this current amplitude Δi.
[0094] It is similar to the above second embodiment that the current amplitude Δi to control the repetition of the regenerative mode and the supply mode can be set almost constant in the overall repeating period of the regenerative mode and the supply mode. Also, the decision method of the inductance (instantaneous inductance) L_m in Eq.(16) is similar to the above second embodiment. In addition, it is similar to the above third embodiment that the current ampli-

tude Δ i can be positively changed with the lapse of time (rotation angle of the rotor) in the repeating period of the regenerative mode and the supply mode.

Fifth Embodiment

[0095] A fifth embodiment of the present invention will be explained with reference to the drawings hereunder. In the above second embodiment, after the supply mode has been executed, the regenerative mode and the reflux mode are executed repeatedly. In the above fourth embodiment, after the supply mode (first supply mode) has been executed, the regenerative mode and the supply mode (second supply mode) are executed repeatedly. In contrast, in this fifth embodiment, above operations are employed in a mixed manner.

[0096] FIGS.13A to 13C are views showing execution timings in respective modes according to a fifth embodiment of the present invention, wherein FIG.13A shows a relationship between the rotation angle of the rotor (abscissa) and the inductance L (ordinate), FIG.13B shows a relationship between the rotation angle of the rotor (abscissa) and the winding voltage (ordinate), and FIG.13C shows a relationship between the rotation angle of the rotor (abscissa) and the winding current (ordinate).

[0097] As shown in FIGS.13A to13C, in the fifth embodiment, the supply mode (first supply mode) is started by turning ON the switching devices SW1, SW2 simultaneously when the rotor is positioned at the predetermined rotation angle θ_{on} in the rising latter half period of the inductance L. Accordingly, the current flowing through the winding is increased. Then, when the winding current (detected current) reaches the predetermined upper limit value i_m at a point of time when the inductance L is turned to fall or in the succeeding falling period, the regenerative mode is executed by turning OFF the switching devices SW1, SW2 at the same time. Accordingly, the winding current is reduced. Then, when the current is reduced from the upper limit value by the predetermined current amplitude Δ i to thus reach the predetermined lower limit value, the supply mode (second supply mode) is executed by turning ON the switching devices SW1, SW2 at the same time. Accordingly, the winding current is increased once again.

[0098] Similarly, when the detected current reaches the predetermined upper limit value and the predetermined lower limit value respectively, the regenerative mode and the supply mode are alternatively executed repetitively (first repeating mode). Then, when the rotation angle of the rotor reaches the predetermined rotation angle or at a point of time when the predetermined number of periods is passed, the regenerative mode and the reflux mode are executed repetitively (second repeating mode). That is, when the current is reduced from the upper limit value by the predetermined current amplitude Δ i to thus reach the predetermined lower limit value after the regenerative mode has been executed, the reflux mode is executed by turning OFF the switching device SW1 and turning ON the switching device SW2, and thus the regenerative mode and the reflux mode are repeated.

[0099] Then, when the rotor is positioned at the predetermined rotation angle θ_{off} (at a point of time prior to a point of time when the inductance L is turned from the falling to the plateau), the repeating control of the regenerative mode and the supply mode is completed. Then, the regenerative mode is executed until the current is reduced to zero.

[0100] Like the above second embodiment, when the regenerative mode and the reflux mode are executed repetitively in the inductance falling period, the execution time of the regenerative mode is shortened to thus undesirably reduce the regenerative amount of energy since increase in the current due to execution of the reflux mode is gentle in the relatively early period (i.e., period during when the inductance is relatively large) of the repeating period. For this reason, in the fifth embodiment, since the current can be increased quickly by executing the supply mode in place of the reflux mode at that time, the execution time of the regenerative mode can be increased correspondingly to thus increase the generation amount of energy. In contrast, since the increase in the current in the supply mode because of the execution of the reflux mode in the relatively late period (i.e., period during when the inductance is relatively small) of the repeating period is quick rather than the period during when the inductance is relatively large, the current can be increased without power consumption by executing not the supply mode but the reflux mode in this period, and thus the power generation amount can be increased as a whole.

[0101] In the fifth embodiment, like the above second embodiment, the upper limit value and the current amplitude Δ i that are the current values to control the mode switching timing are employed in the repeating period in which the regenerative mode and the supply mode are repeated. Thus, it is the same as the above second embodiment that the smaller current amplitude Δ i is advantageous to the SR motor. Therefore, since its control is almost similar, explanation will be omitted. As with above respective equations in connection with the current amplitude Δ i at this time, the equations discussed in the above fourth embodiment are employed in the first repeating mode in which the regenerative mode and the supply mode are repeated, while the equations discussed in the above second embodiment are employed in the second repeating mode in which the regenerative mode and the reflux mode are repeated.

[0102] It is similar to the above second embodiment that the current amplitude Δ i for the repetition control can be set almost constant in the overall repeating period of the regenerative mode and the supply mode. Also, it is similar to the above third embodiment that the current amplitude Δi can be positively changed with the lapse of time (rotation angle of the rotor) in the repeating period of the regenerative mode and the supply mode.

Sixth Embodiment

[0103] A sixth embodiment of the present invention will be explained with reference to the drawings hereunder. This sixth embodiment intends to optimize a start timing of the supply mode or the first supply mode, which is finished at the same time when the repetition mode is started (referred also to as the initial supply mode hereinafter) and a start timing of the regenerative mode, which is started at the same time when the repetition mode is finished (referred also to as the last regenerative mode hereinafter) in the above second to fifth embodiments, from the viewpoint of increasing the power generation amount.

[0104] FIGS.14A and 14B are views showing start timings of the initial supply mode according to the sixth embodiment of the present invention, wherein FIG.14A shows a relationship between the rotation angle of the rotor (abscissa) and the inductance L (ordinate), and FIG.14B shows a relationship between the rotation angle of the rotor (abscissa) and the winding current (ordinate). FIG.15 is a graph showing a relationship between start timings in the supply mode and the power generation amount if the first current value is set variously in the sixth embodiment of the present invention. FIGS.16A and 16B are views showing start timings of the last regenerative mode in the sixth embodiment of the present invention, wherein FIG.16A shows a relationship between the rotation angle of the rotor (abscissa) and the inductance L (ordinate), and FIG.16B shows a relationship between the rotation angle of the rotor (abscissa) and the winding current (ordinate).

[0105] First, FIGS.14A and 14B are referred to hereunder. The initial supply mode is started when the rotor reaches the certain angle θ_{on} , and the current flowing through the winding is increased. Then, the initial supply models ended and at the same time the repetition mode is started when the current reaches the predetermined upper limit value i_m. In the repetition mode, the regenerative mode and the reflux or the supply mode (second supply mode) are repeated. Then, the repetition mode is terminated and at the same time the last regenerative mode is started when the rotor reaches the certain angle θ_{off} . Thus, the current flowing through the winding is reduced finally to zero and then one period of this control method is finished. Here, the power generation amount can be derived as a difference between the total regenerative power in the regenerative mode and the supply power in the supply mode.

[0106] For this reason, if the predetermined upper limit value i_m of the current is decided, a start timing θ_{on} of the initial supply mode serves as an important factor to affect the power generation amount. If this start timing θ_{on} of the initial supply mode is set between $0<\theta_{on}<\theta_1$, it is possible to accelerate the rising of the current and also reduce the supply power because such timing is positioned in the inductance reducing period. Where the rotation angle of the rotor is set to 0 (zero) at a point of time when a period in which the winding inductance is lowered as the rotor rotates is started, i.e., when the winding inductance reaches the maximum inductance L_1, and the rotation angle of the rotor is set to θ_1 at a point of time when the period in which the winding inductance is lowered as the rotor rotates is ended, i.e., when the winding inductance reaches the minimum inductance L_0.

[0107] However, since the regenerative/reflux (or supply) repeating period is shortened by the initial supply mode if θ_{on} is set in the above range, the regenerative power is reduced and as a result the power generation amount is reduced. Therefore, if the start angle θ_{on} is leaded toward the direction of $\theta_{on} < 0$, the regenerative/reflux repeating period is extended and thus the regenerative power can be increased. In this case, if the start angle θ_{on} is too leaded, the rising of the current becomes slow to thus increase the supply power since the start angle is located in the inductance increasing period. As a result, the power generation amount is also reduced. It can be understood based on the above that a balance of the supply power and the regenerative power is changed according to the start angle θ_{on} and thus an optimum value of θ_{on} is present to maximize the power generation amount.

[0108] As shown in FIG.14B, the optimum value range is given as $\theta\ on_1 \leq \theta\ on \leq \theta\ on_2$. An angle $\theta\ on_2$ is an angle at which the winding inductance is started to reduce as the rotor rotates, and coincides with 0 in FIG.14B. An angle $\theta\ on_1$ is an angle which provides an ON timing after which the current reaches the predetermined upper limit value i_m at $\theta\ on = \theta on_2 (=0)$.

[0109] FIG.11 shows simulation results of the power generation amount when the ON timing θ_{on} is changed, and shows the cases where the current upper limit value is set to 6. 7, 8 A respectively. In FIG.11, the abscissa denotes the rotation angle θ (degree) of the rotor, and the ordinate denotes the power generation amount (W) per phase. The rotation angle θ=0 of the rotor provides a state in which the salient pole of the stator and the salient pole of the rotor face perfectly each other, i.e., a middle point of the top end of the salient pole of the stator along the rotor rotation direction and a middle point of the top end of the salient pole of the rotor along the rotor rotation direction are positioned opposite to each other. In FIG.15, an angle range from θ=0 as a reference to another angle (leftside position) indicated by the bidirectional arrow gives the ON timing which satisfies the winding current can reach the upper limit value i_m at θ =0. As evident from FIG.15, it can be checked that θ_{on} - to maximize the power generation amount for each current upper limit value is located in the range in FIG.15 indicated by the bidirectional arrow. It can be understood that the highly effective power generation can be achieved by starting the initial supply mode (by turning ON the switching devices SW1, SW2 simultaneously) within this range (from $\theta\ on_1$ to $\theta\ on_2$).

[0110] Then, like the above start timing (θ on) of the initial supply mode, a start timing θ_{off} of the last regenerative

mode is an important factor to affect the power generation amount. If θ_{off} is lagged rather than θ_1, the regenerative power can be increased. However, since the start timing θ_{off} is located in the constant inductance period, the falling of the current is accelerated and also the regenerative power in the last regenerative mode is reduced. As a result, the power generation amount is reduced.

[0111] In contrast, if θ_{off} is leaded rather than θ_1, the rising of the current becomes slow and the regenerative power in the last regenerative mode can be increased since the start timing θ_{off} is located in the inductance reducing period. If θ_{off} is too leaded, the regenerative/reflux (or supply) repeating period is shortened and as a result the power generation amount is also reduced. It can be understood based on the above that the optimum value of θ_{off} is present to maximize the power generation amount.

[0112] As shown in FIG.16B, the optimum value range is given as $0\ off_1 \leqq \theta\ off \leqq \theta\ off_2$. An angle $\theta\ off_2$ is an angle at which the winding inductance starts to be the minimum constant value as the rotor rotates, and coincides with θ_1 in FIG.16B. An angle $\theta\ off_1$ is an angle which provides an OFF timing after which the current reaches 0 at the rotation angle of the rotor $\theta = \theta\ off_2 (=0_1)$. It can be understood that highly effective power generation can be achieved by starting the last regenerative mode (by turning OFF the switching devices SW1, SW2 simultaneously) within the range from $\theta\ off_1$ to θoff_2.

[0113] As described above, the power generation amount can be maximized by controlling the start timing (angle) θ_{on} of the initial supply mode and the start timing (angle) θ_{off} of the last regenerative mode into the optimum value range respectively.

[0114] Since the inductance waveform in the actual motor is not formed as the chopping waveform having shape edges shown until now (formed as a waveform having rounded edges), the angle $\theta\ on_2$ at which reduction of the inductance starts and the angle $\theta\ off_2$ at which the inductance comes close to the minimum value cannot be defined precisely. In this case, ideally the inductance waveform can be derived from the motor shape and these angles can be given by following equations.

$\theta\ on_2$={(circular arc angle θ_R of the salient pole of the rotor)-(circular arc angle θ_S of the salient pole of the stator)}/2

$\theta\ off_2$={(circular arc angle θ_R of the salient pole of the rotor)+(circular arc angle θ_S of the salient pole of the stator)}/2

[0115] Also, in the motor in which the inductance waveform becomes the trapezoidal waveform, as shown in FIG.17. for example, these angles can be defined according to these equations.

[0116] In this manner, the angle $\theta\ on_2$ at which the period during when the inductance of the rotor is reduced as the rotor rotates is started and the angle $\theta\ off_2$ at which the period during when the inductance of the rotor is reduced as the rotor rotates is ended can be obtained by calculation.

[0117] Next, there will be explained hereunder a method of detecting the start angle $\theta\ on_1$ of the supply mode which satisfies that the winding current reaches the upper limit value i_m at the angle θ=0 of the rotor and the start angle $\theta\ off_1$ of the last regenerative mode which satisfies that the winding current reaches zero at the angle $\theta = \theta_1$ of the rotor, by calculation based on the power supply voltage, motor constants, the rotation speed, and the predetermined upper limit value i_m of the current.

[0118] First, the start angle $\theta\ on_1$ is obtained. If the initial supply mode is started in the period in which the winding inductance is increased as the rotor rotates, the current value at the angle θ can be given by the following equation based on the circuit equation under the assumption that the inductance is approximated by the chopping waveform as shown in FIG.14A.

$$i = \frac{E/R}{1+A}\left[1-\left[\frac{L_1+K_L\theta}{L_1+K_L\theta_{on}}\right]^{-\left(\frac{1+A}{A}\right)}\right] \qquad \ldots (17)$$

where $K_L = (L_1 - L_0)/\theta_1$ and $A = K_L \cdot \omega/R$.

[0119] Here, L_1 is the maximum inductance of the winding, L_0 is the minimum inductance of the winding, R is the resistance of the winding, E is the power supply voltage, i_m is the predetermined upper limit value of the current, and ω

is the rotation speed. Also, if the rotor angle which gives the inductance L_1 or the rotor angle at which the salient pole of the stator faces perfectly to the salient pole of the rotor is set to $\theta = 0$, θ_1 is given as the angle at which the winding inductance starts to be the minimum value as the rotor rotates or the angle which is calculated by {(circular arc angle θ_R of the salient pole of the rotor) + (circular arc angle θ_S of the salient pole of the stator)}/2 .

[0120] After substituting the condition of $\theta\ on_1$, i.e., the winding current $i = i_m$ at the rotor angle $\theta = 0$ into Eq.(17), $\theta\ on_1$ can be calculated by solving θ on.

$$\theta_{on1} = \frac{L_1}{K_L}\left[\left[1-\frac{(1+A)\cdot R\cdot i_m}{E}\right]^{\frac{A}{1+A}}-1\right] \qquad \ldots(18)$$

[0121] Accordingly, when the power supply voltage E, the motor constants, the rotation speed ω and the predetermined upper limit value i_m of the current are given, it is possible to maximize the power generation amount for any θ_{off} by controlling θ_{on} within the range given by following equation.

$$\frac{L_1}{K_L}\left[\left[1-\frac{(1+A)\cdot R\cdot i_m}{E}\right]^{\frac{A}{1+A}}-1\right] \leq \theta_{on} \leq 0 \qquad \ldots(19)$$

[0122] Then, the start angle $\theta\ off_1$ is obtained. If the last regenerative mode is started in the period in which the winding inductance is reduced as the rotor rotates, the current value at the angle θ can be given by the following equation based on the circuit equation under the assumption that the inductance is approximated by the chopping waveform as shown in FIG.14A and also the current amplitude Δi is sufficiently small in contrast to the predetermined upper limit value i_m.

$$i = \frac{E/R}{A-1} - \left[\frac{E/R}{A-1} - i_m\right]\left[\frac{L_1 - K_L\theta}{L_1 - K_L\theta_{off}}\right]^{-\left(\frac{A-1}{A}\right)} \qquad \ldots(20)$$

where $K_L = (L_1 - L_0)/\theta_1$ and $A = K_L \cdot \omega/R$.

[0123] Here, L_1 is the maximum inductance of the winding, L_0 is the minimum inductance of the winding, R is the resistance of the winding, E is the power supply voltage, i_m is the predetermined upper limit value of the current, and ω is the rotation speed. Also, if the rotor angle which gives the inductance L_1 or the rotor angle at which the salient pole of the stator faces perfectly to the salient pole of the rotor is set to $\theta = 0$, θ_1 is given as the angle at which the winding inductance starts to be the minimum value as the rotor rotates or the angle which is calculated by {(circular arc angle θ_R of the salient pole of the rotor) + (circular arc angle θ_S of the salient pole of the stator)}/2 . After substituting the condition of $\theta\ off_1$, i.e., the winding current $i = 0$ at the rotor angle $\theta = \theta_1$ into Eq.(20), $\theta\ off_1$ can be calculated by solving θ off.

$$\theta_{off1} = \frac{1}{K_L}\left[L_1 - (L_1 - K_L\theta_1)\left[\frac{E}{E + (1-A)\cdot R\cdot i_m}\right]^{\frac{A}{A-1}}\right] \quad \ldots(21)$$

[0124] Accordingly, when the power supply voltage E, the motor constants, the rotation speed ω and the predetermined upper limit value i_m of the current are given, it is possible to maximize the power generation amount for any θ_{on} by controlling θ_{off} within the range given by following equation.

$$\frac{1}{K_L}\left[L_1 - (L_1 - K_L\theta_1)\left[\frac{E}{E + (1-A)\cdot R\cdot i_m}\right]^{\frac{A}{A-1}}\right] \le \theta_{off} \le \theta_1 \quad \ldots(22)$$

[0125] The above-mentioned embodiments are set forth to make the understanding of the present invention easy, and are not set forth to limit the present invention. Therefore, respective elements disclosed on the above embodiments should be interpreted to include all design changes and equivalents which belong to the technical range of the present invention.

[0126] For example, the number of the salient poles of the stator and the rotor and the number of phase are not limited to those in the above embodiments, and others may be applied similarly.

[0127] It should be understood that many modifications and adaptations of the invention will become apparent to those skilled in the art and it is intended to encompass such obvious modifications and changes in the scope of the claims appended hereto.

Claims

1. A method of controlling an SR motor which includes a stator (3) having a plurality of salient poles (3a) with windings (7) therearound generating magnetic fields therein, and a rotor (2) having another plurality of salient poles (2a), the method comprising executing, changeably as the rotor (2) rotates, a supply mode for supplying power from a power supply (E) to the windings (7), a reflux mode for setting both terminals of the windings (7) to an identical potential, and a regenerative mode for recovering electromotive force generated in the windings (7) into the power supply (E).

2. A method according to claim 1, wherein the supply mode, the reflux mode, and the regenerative mode are executed in that order.

3. A method according to claim 2, wherein the supply mode starts in a period in which inductance (L) of the windings (7) rises as the rotor (2) rotates, and the reflux mode replaces the supply mode in a period in which the inductance (L) of the windings (7) is reduced as the rotor (2) rotates.

4. A method according to claim 3, wherein, after the reflux mode replaces the supply mode, the regenerative mode replaces the reflux mode before the end of the period in which the inductance (L) of the windings (7) is reduced as the rotor (2) rotates.

5. A method according to claim 1, wherein the reflux mode replaces the supply mode when the rotation angle (θ) of the rotor (2) reaches a predetermined first angle, and the regenerative mode replaces the reflux mode when the rotation angle θ reaches a predetermined second angle.

6. A method according to claim 1, wherein the reflux mode replaces the supply mode when a current (i) flowing through the windings (7) reaches a predetermined first current value, and the regenerative mode replaces the

reflux mode when the current (i) reaches a predetermined second current value higher than the first.

7. A method according to claim 1, wherein after the supply mode is executed, a repetitive mode during which the regenerative mode and the reflux mode are repeated alternatively is executed.

8. A method according to claim 7, wherein the repetitive mode is executed in a period in which inductance (L) of the windings (7) is reduced as the rotor (2) rotates.

9. A method according to claim 7, wherein a current (i) flowing through the windings (7) is detected, and, in the repetitive mode the regenerative mode is executed when the detected current (i) reaches a first current value, and the reflux mode is executed when the detected current (i) reaches a second current value lower than the first.

10. A method according to claim 7, wherein a switching period of the repetitive mode in which the regenerative mode and the reflux mode are switched is constant, and the current value flowing through the windings (7) is controlled to change a ratio of a period of the regenerative mode to a period of the reflux mode in each switching period while keeping the switching period constant.

11. A method according to claim 7, wherein the repetitive mode is executed only when the number of rotations of the rotor per unit time is larger than $-R/(dL/d\theta)$,where R is resistance of the windings and $(dL/d\theta)$ is a rate of change of the inductance of the windings.

12. A method according to claim 9, wherein the first current value is set to be a value smaller than $-E/(R + (dL/d\theta) \cdot \omega)$,
where ω is a number of rotations of the rotor per unit time and E is a power supply voltage.

13. A method according to claim 12, wherein a current amplitude Δi which is a difference between the first current value and the second current value is set to satisfy $\Delta t \geqq \Delta t_0$, where Δt is a current change period in the repeating period in which the repetitive mode is executed, and Δt_0 to is a minimum switching period of switching means connected to the windings to switch a mode.

14. A method according to claim 13, wherein the current amplitude Δi is decided by

$$\Delta t = \Delta i \cdot EL_m/(\alpha(E-\alpha)),$$

where $\alpha = -(R + \omega(dL/d\theta))i_m$, and R is winding resistance, ω is a number of rotations of the rotor per unit time, E is a power supply voltage, i_m is the first current value, L_m is an instantaneous inductance of the windings, and $(dL/d\theta)$ is a rate of change of the inductance of the windings.

15. A method according to claim 13, wherein the current amplitude Δi is set constant over the entire repeating period.

16. A method according to claim 15, wherein minimum inductance of the windings is used as the instantaneous Inductance L_m in an equation to calculate the current amplitude Δi.

17. A method according to claim 15, wherein inductance of the windings at an end point of time of the repeating period is used as the instantaneous inductance L_m in an equation to calculate the current amplitude Δi.

18. A method according to claim 15, wherein inductance of the windings obtained when a rotation angle of the rotor is given by $\theta_{off} - (\Delta t/2) \cdot \omega$ is used as the instantaneous inductance Lm in an equation to calculate the current amplitude Δi, where θ_{off} is a rotation angle of the rotor at an end point of time of the repeating period.

19. A method according to claim 13, wherein the current amplitude Δi is changed depending upon the rotation angle of the rotor such that the current change period in the repeating period becomes constant.

20. A method of controlling an SR motor which includes a stator (3) having a plurality of salient poles (3a) with windings (7) therearound generating magnetic fields therein, and a rotor (2) having another plurality of salient poles (2a), the method comprising executing a first supply mode for supplying power from a power supply (E) to the windings (7); and then executing a repetitive mode during which a regenerative mode for recovering electromotive force generated in the windings (7) into the power supply (E) and a second supply mode for supplying power from the power

supply (E) to the windings (7) are repeated alternatively.

21. A method according to claim 20, wherein the repetitive mode is executed in a period in which inductance (L) of the windings (7) is reduced as the rotor (2) rotates.

22. A method according to claim 20, wherein, after the first supply mode is executed, a first repetitive mode during which the regenerative mode and the second supply mode are repeated alternately and a second repetitive mode during which the regenerative mode and a reflux mode for setting both terminals of the windings (7) to an identical potential are repeated alternately, are mixedly executed.

23. A method according to claim 22, wherein the first repetitive mode and the second repetitive mode are executed in that order in a period in which inductance (L) of the windings (7) is reduced as the rotor (2) rotates.

24. A method according to claim 20 or 22, wherein a current (i) flowing through the windings (7) is detected, and, in the first or second repetitive mode, the regenerative mode is executed when the detected current (i) reaches a first current value, and the reflux mode or the second supply mode is executed when the detected current (1) reaches a second current value lower than the first.

25. A method according to claim 20 or 22, wherein a switching period in which the regenerative mode and the reflux mode are switched is set constant in the repetitive mode, and the current value flowing through the windings (7) is controlled by changing a ratio between a regenerative mode time and a reflux mode or second supply mode time in one switching period.

26. A method according to claim 24, wherein a current amplitude Δ i which is a difference between the first current value and the second current value is set to satisfy $\Delta t \geqq \Delta t_o$ where Δt is a current change period in the repeating period in which the repetitive mode is executed, and Δt_o is a minimum switching period of switching means connected to the windings to switch a mode.

27. A method according to claim 26, wherein the current amplitude Δ i is decided by

$$\Delta t = \Delta i \cdot 2EL_m/(E^2 - \alpha^2)$$

where $\alpha = -(R + \omega(dL/d\theta))\, i_m$, R is winding resistance, ω is a number of rotations of the rotor per unit time, E is a power supply voltage, i_m is the first current value, L_m is an instantaneous inductance of the windings, and $dL/d\theta$ is a rate of change of the inductance of the windings.

28. A method according to claim 26, wherein the current amplitude Δ i is set constant over the entire repeating period.

29. A method according to claim 28, wherein minimum inductance of the windings is used as the instantaneous inductance L_m in an equation to calculate the current amplitude Δ i.

30. A method according to claim 28, wherein inductance of the windings at an end point of time of the repeating period is used as the instantaneous inductance L_m in an equation to calculate the current amplitude Δ i.

31. A method according to claim 28, wherein inductance of the windings obtained when a rotation angle of the rotor is given by θ_{off}-(Δ t/2) $\cdot$ ω is used as the instantaneous inductance Lm in an equation to calculate the current amplitude Δ i, where θ_{off} is a rotation angle of the rotor at an end point of time of the repeating period.

32. A method according to claim 26, wherein the current amplitude Δ i is changed depending upon the rotation angle of the rotor such that the current change period in the repeating period becomes constant.

33. A method according to claim 32, wherein the current amplitude Δ i is linearly changed from Δi_1 to Δi_0 as the rotation angle of the rotor changes from θ_m to θ_{off}, where Δi_1 is the current amplitude calculated by using the inductance at the rotation angle θ_m of the rotor when the current of the windings reaches first the first current value as the instantaneous inductance L_m in an equation to calculate the current amplitude Δ i, and Δi_0 is the current amplitude calculated by using the inductance at the rotation angle θ_{off} of the rotor at an end point of time of the repeating period as the instantaneous inductance L_m in an equation to calculate the current amplitude Δ i.

34. A method according to claim 7, 20 or 22, wherein the supply mode or the first supply mode is started at an angle prior to a start angle at which the period during which the inductance of the windings is reduced is started and at the angle such that the current flowing through the windings reaches the first current value in a period during which the inductance of the windings is reduced as the rotor rotates.

35. A method according to claim 34, wherein an angle represented by $(\theta_R - \theta_S))/2$ is used as an angle at which a period during which the inductance is reduced is started, where θ_R is a circular arc angle of a salient pole of the rotor, θ_S is a circular arc angle of a salient pole of the stator, and the angle of the rotor at a point of time when the salient pole of the stator and the salient pole of the rotor face perfectly to each other is set to zero.

36. A method according to claim 35, wherein the start angle θ_{on} of the supply mode or the first supply mode is set in a range represented by

$$\frac{L_1}{K_L}\left[\left[1-\frac{(1+A)\cdot R\cdot i_m}{E}\right]^{\frac{A}{1+A}}-1\right]\le\theta_{on}\le 0$$

where $K_L = (L_1 - L_0)/\theta_1$, $A = K_L \cdot \omega/R$, L_1 is maximum inductance of the windings, L_0 is minimum inductance of the windings, R is resistance of the windings, E is a power supply voltage, i_m is a first current value, ω is a rotation speed, and an angle at which a period during which the inductance of the windings is reduced is started is 0, and an angle at which the period is ended is θ_1.

37. A method according to claims 7, 20 or 22, wherein the last regenerative mode which is started at a same time when the repetitive mode is ended is started at an angle prior to an end angle at which the period during which the inductance of the windings is reduced is ended and at the angle such that the current flowing through the windings reaches zero after a period during which the inductance of the windings is reduced as the rotor rotates has been lapsed.

38. A method according to claim 37, wherein an angle represented by $(\theta_R + \theta_S)/2$ is used as an angle at which a period during when the inductance is reduced is ended, where θ_R is a circular arc angle of a salient pole of the rotor, θ_S is a circular arc angle of a salient pole of the stator, and the angle of the rotor at a point of time when the salient pole of the stator and the salient pole of the rotor face perfectly to each other is set to zero.

39. A method according to claim 37, wherein the start angle θ_{off} of the last regenerative mode is set in a range represented by

$$\frac{1}{K_L}\left[L_1-(L_1-K_L\theta_1)\left[\frac{E}{E+(1-A)\cdot R\cdot i_m}\right]^{\frac{A}{A-1}}\right]\le\theta_{off}\le\theta_1$$

where $K_L = (L_1 - L_0)/\theta_1$, $A = K_L \cdot \omega/R$, L_1 is maximum inductance of the windings, L_0 is minimum inductance of the windings, R is resistance of the windings, E is a power supply voltage, i_m is a first current value, ω is a rotation speed, and an angle at which a period during which the inductance of the windings is reduced is started is O, and an angle at which the period is ended is θ_1.

40. An SR motor comprising a stator (3) having a plurality of salient poles (3a) with windings (7) therearound for generating magnetic fields therein, and a rotor (2) having another plurality of salient poles (2a) the SR motor including: a first switch (SW1) configured to connect selectively a start terminal (T1) of a set of windings (C) to one polarity (E) of a power supply; a second switch (SW2) configured to connect selectively an end terminal (T2) of the set windings (C) to the other polarity (GND) of the power supply; a first diode (D1) interposed between the start terminal (T1) and the said other polarity (GND) and configured to pass a current only in a direction toward the start ter-

minal (T1); a second diode (D2) interposed between the end terminal (T2) and the said one polarity (E) and configured to pass a current only in a direction toward the said one polarity (E); and a controller (12) configured to control to execute, changeably as the rotor (2) rotates, a supply mode in which the first switch (SW1) and the second switch (SW2) are both connected, a reflux mode in which one of the switches (SW1, SW2) is connected and other is cut off, and a regenerative mode in which the switches (SW1 SW2) are both cut off.

41. An SR motor according to claim 40, wherein the controller (12) executes the supply mode, the reflux mode, and the regenerative mode in that order.

42. An SR motor according to claim 40, wherein after the supply mode is executed, a repetitive mode during which the regenerative mode and the reflux mode are repeated alternately is executed.

43. An SR motor according to claim 42, further comprising:

a current detector (11) configured to detect the current flowing through the windings (C), wherein the controller (12) controls to execute the regenerative mode when a detection current detected by the current detector (11) reaches a first current value and to execute the reflux mode when the detection current reaches a second current value which is lower than the first.

44. An SR motor according to claim 43, wherein the controller (12) sets a current amplitude Δ i which is a difference between the first current value and the second current value to satisfy $\Delta t \geqq \Delta t_0$, where Δ t is a current change period in a repeating period during which the regenerative mode and the reflux mode are repeated, and Δt_0 is a minimum switching period of the first switch (SW1) and the second switch (SW2).

45. An SR motor according to claim 44, wherein the current amplitude Δ i is set constant over the entire repeating period.

46. An SR motor according to claim 44, wherein the current amplitude Δ i is changed depending upon a rotation angle of the rotor (2) such that the current change period in the repeating period becomes constant.

47. An SR motor according to claim 43, wherein the supply mode is started at an angle prior to a start angle at which the period during which the inductance of the windings (C) is reduced is started or at the angle such that the current flowing through the windings (C) reaches the first current value in a period during which the inductance of the windings is reduced as the rotor (2) rotates.

48. An SR motor according to claim 43, wherein the last regenerative mode which is started at a same time when the repetitive mode is ended is started at an angle prior to an end angle at which the period during which the inductance of the windings (C) is reduced is ended or at the angle such that the current flowing through the windings (C) reaches zero after a period during which the inductance of the windings (C) is reduced as the rotor (2) rotates has elapsed.

49. An SR motor comprising a stator (3) having a plurality of salient poles (3a) with windings (7) therearound for generating magnetic fields therein, and a rotor (2) having another plurality of salient poles (2a), the SR motor including: a first switch (SW1) configured to connect selectively a start terminal (T1) of a set of windings (C) to one polarity (E) of a power supply; a first diode (D1) interposed between the start terminal (T1) and the said other polarity (GND) and configured to pass a current only in a direction toward the start terminal (T1); a second diode (D2) interposed between the end terminal (T2) and the said one polarity (E) and configured to pass a current only in a direction toward the said one polarity (E); and a controller (12) configured to control to execute a first supply mode in which the first switch (SW1) and the second switch (SW2) are both connected, and then execute a repetitive mode in which the switches (SW1), are both cut off and a second supply mode in which the switches (SW1, SW2) are both connected.

50. An SR motor according to claim 40, wherein after a first supply mode is executed, a first repetitive mode during which the regenerative mode and a second supply mode are repeated alternately and a second repetitive mode during which the regenerative mode and the reflux mode are repeated alternately are mixedly executed.

FIG. 1A
PRIOR ART

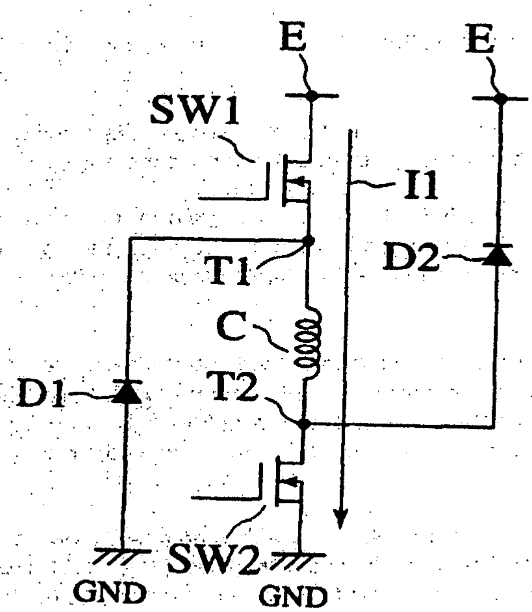


FIG. 1B
PRIOR ART

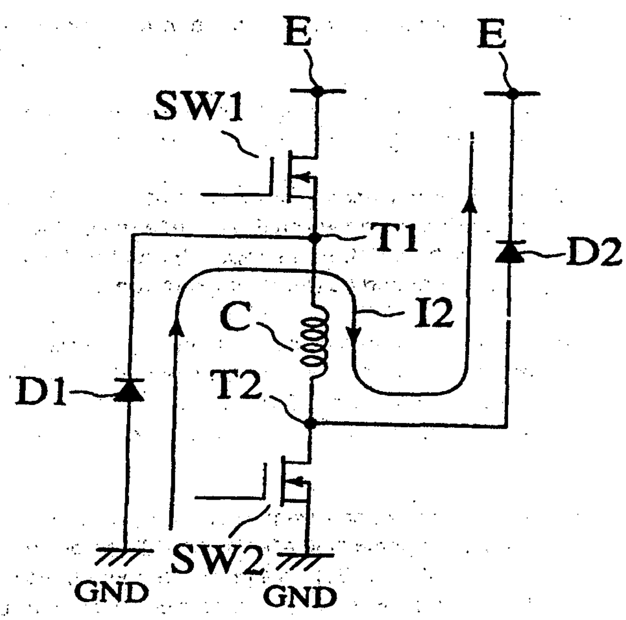


FIG. 2A
PRIOR ART

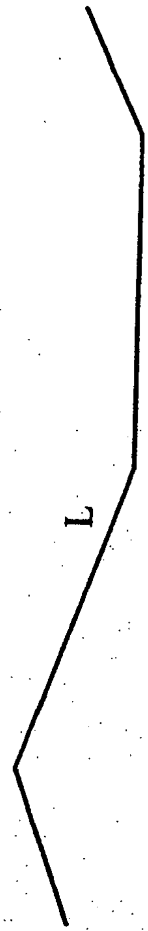


FIG. 2B
PRIOR ART

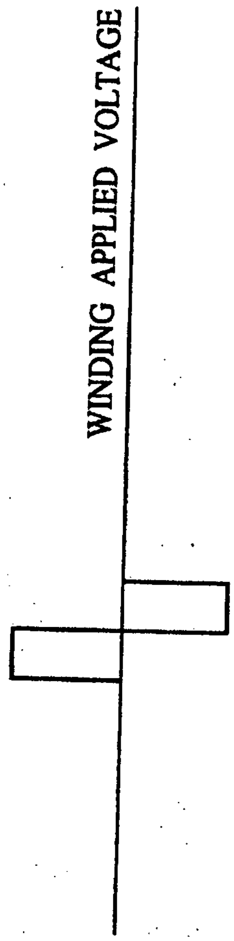


FIG. 2C
PRIOR ART

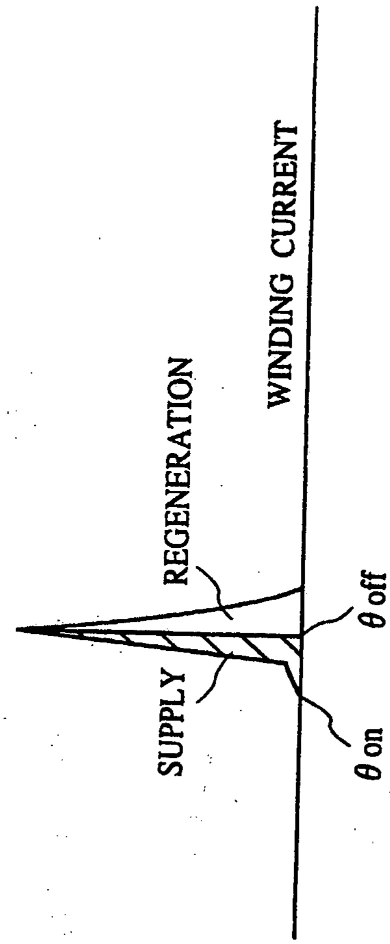


FIG. 3A
PRIOR ART

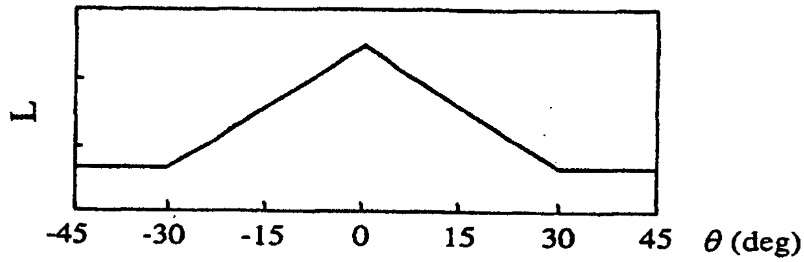


FIG. 3B
PRIOR ART

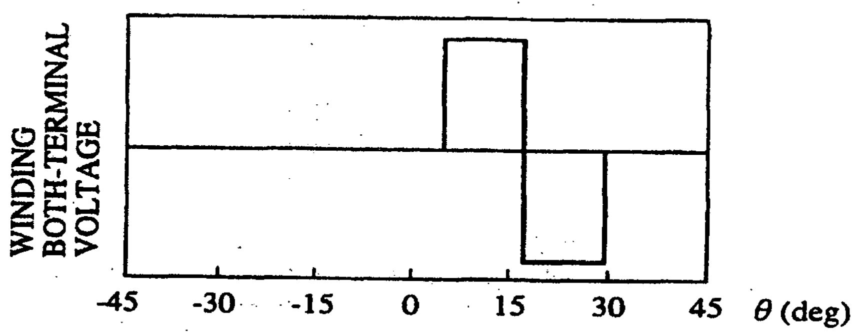


FIG. 3C
PRIOR ART

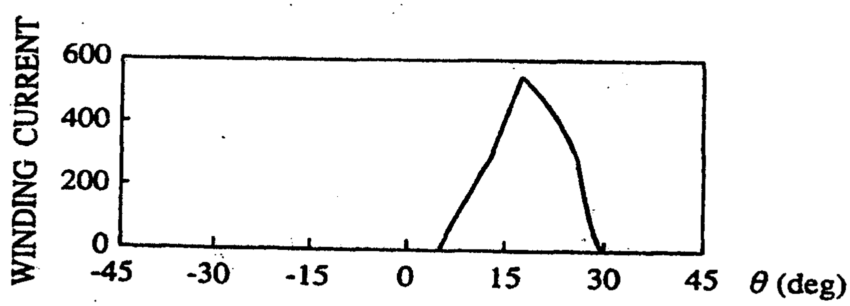


FIG. 3D
PRIOR ART

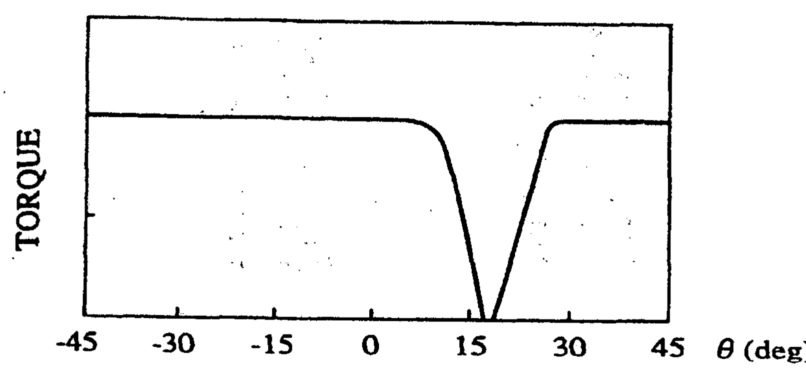


FIG. 4

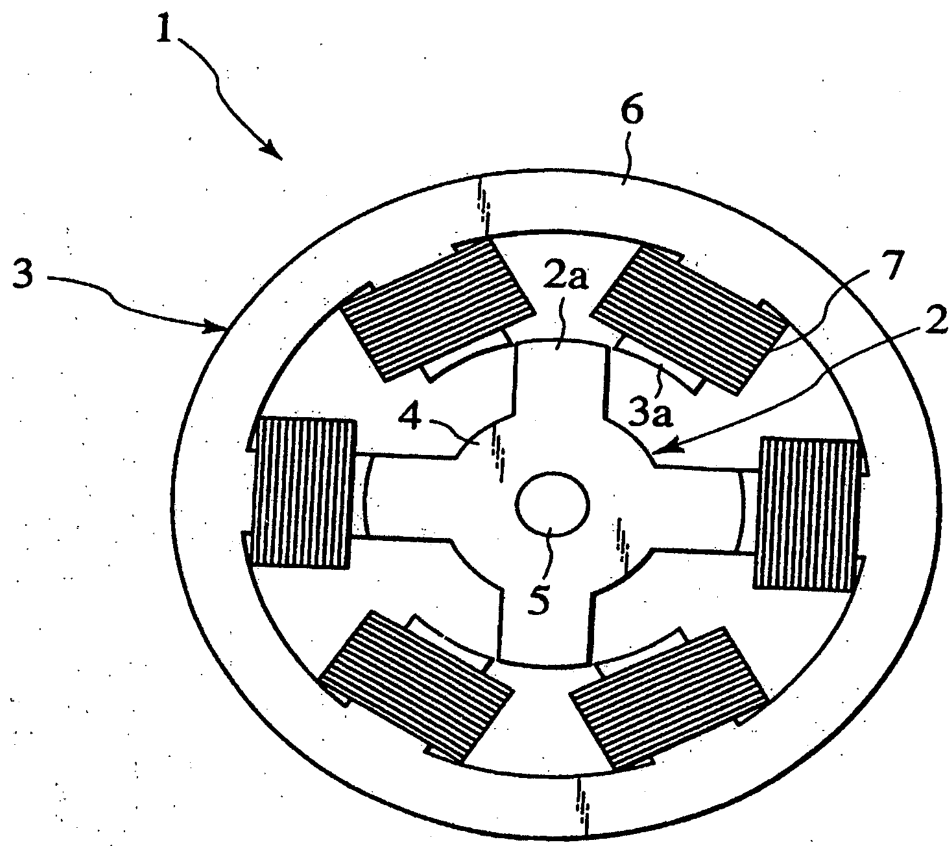


FIG. 5A

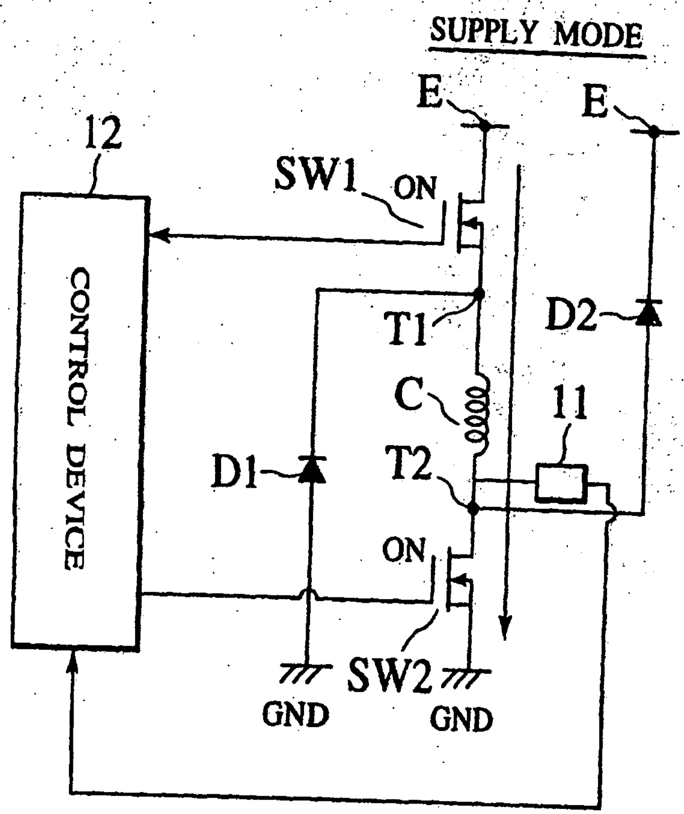


FIG. 5B

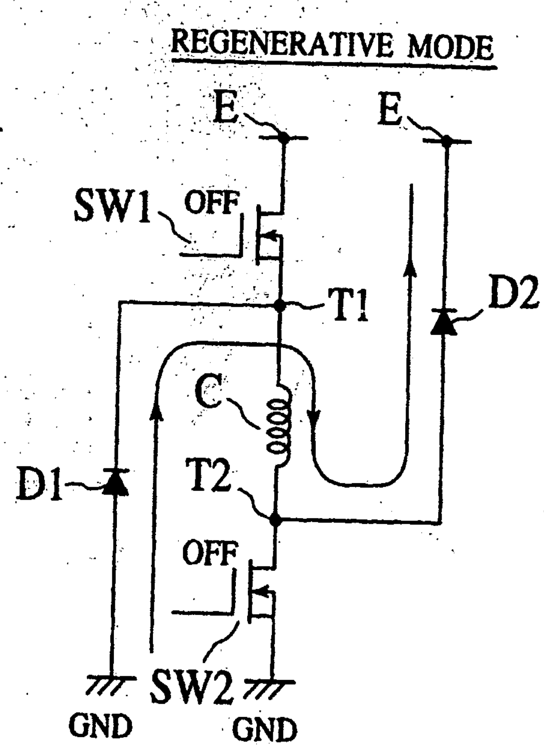


FIG. 5C

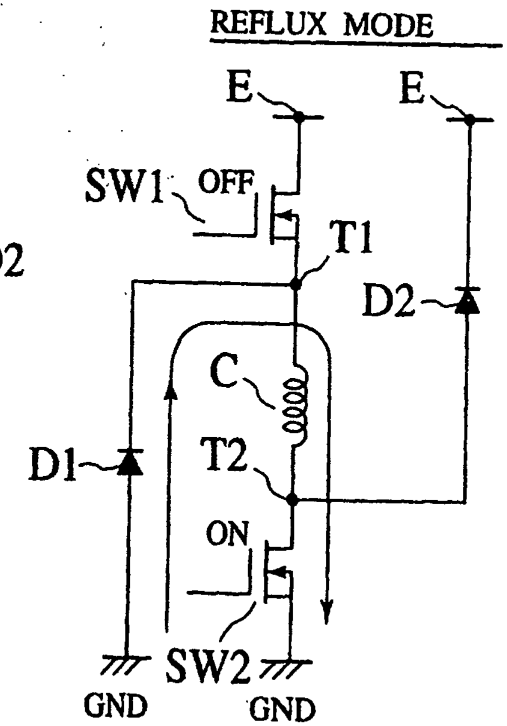


FIG. 6A

FIG. 6B

FIG. 6C

FIG. 6D

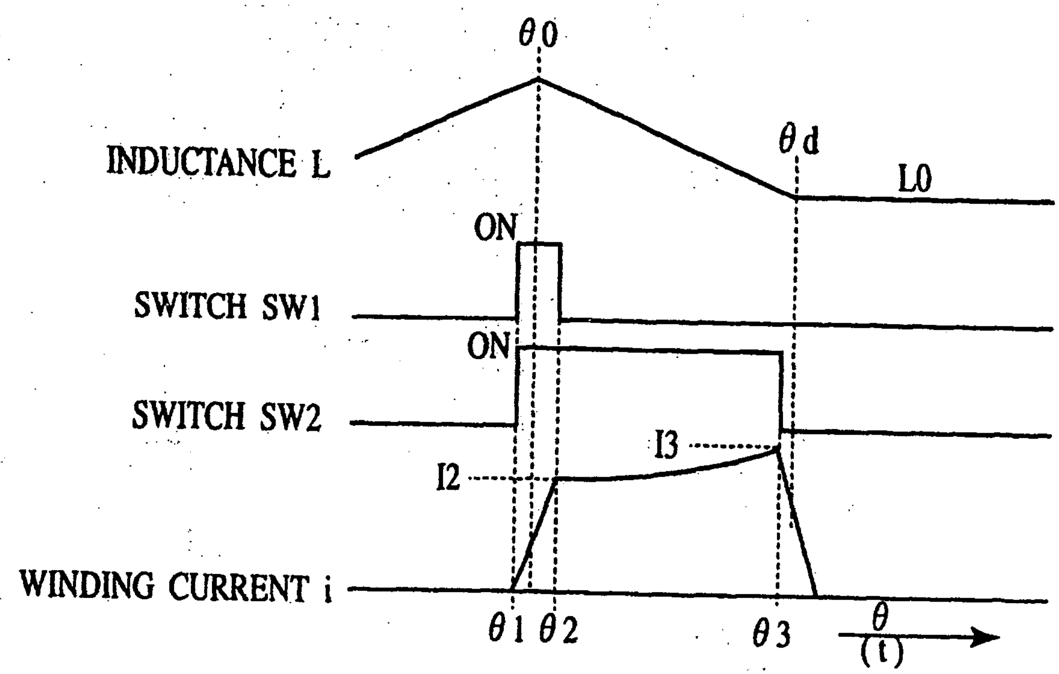


FIG. 7A

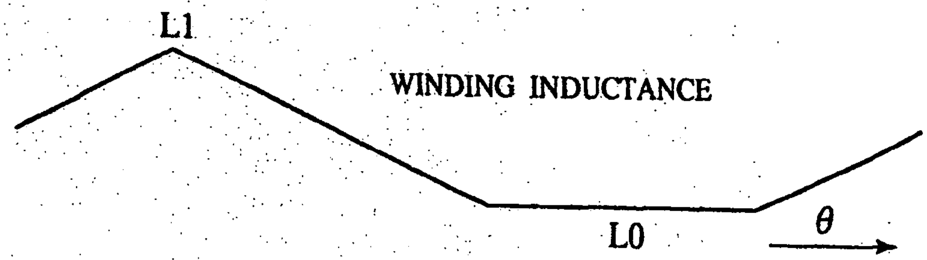


FIG. 7B

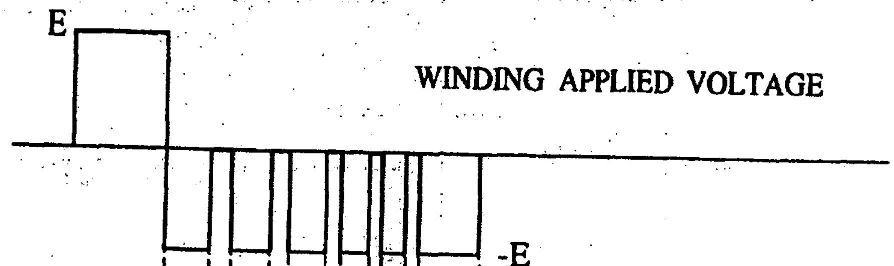


FIG. 7C

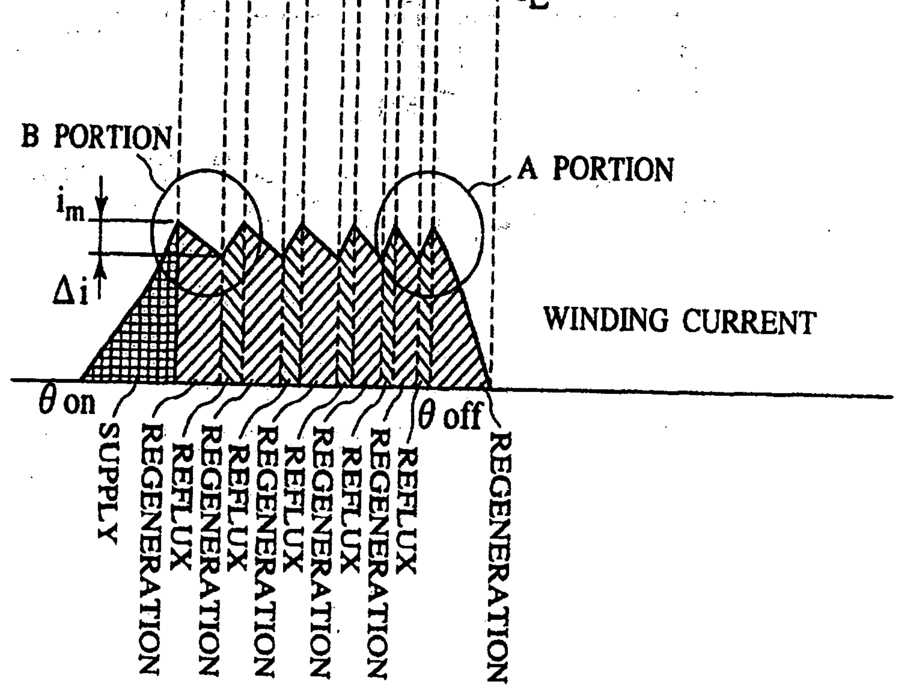


FIG. 8A

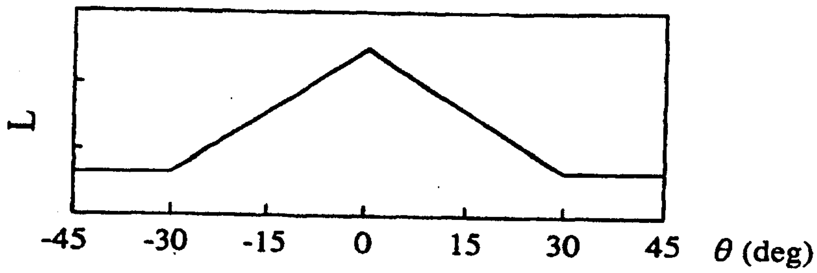


FIG. 8B

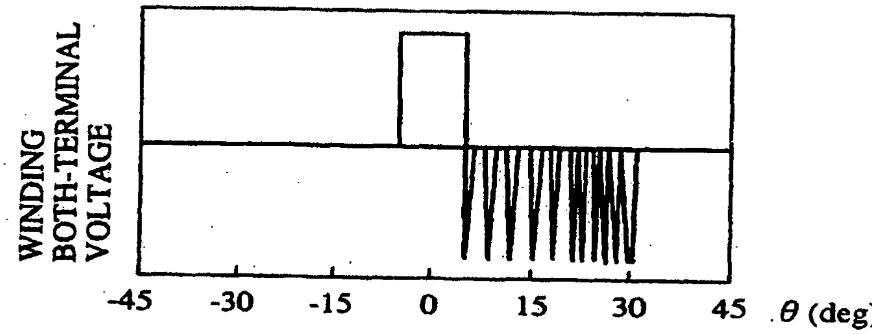


FIG. 8C

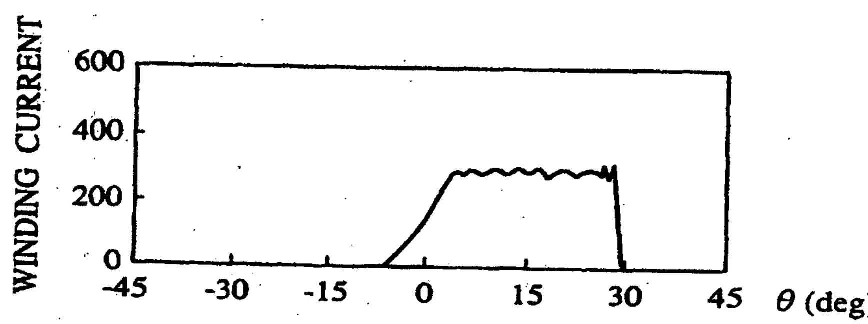


FIG. 8D

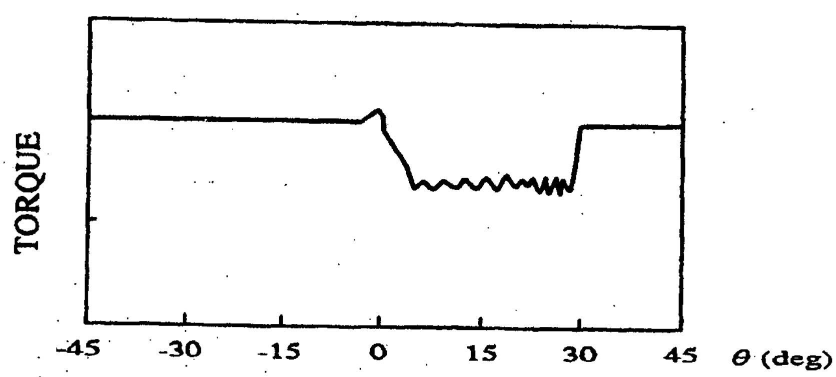
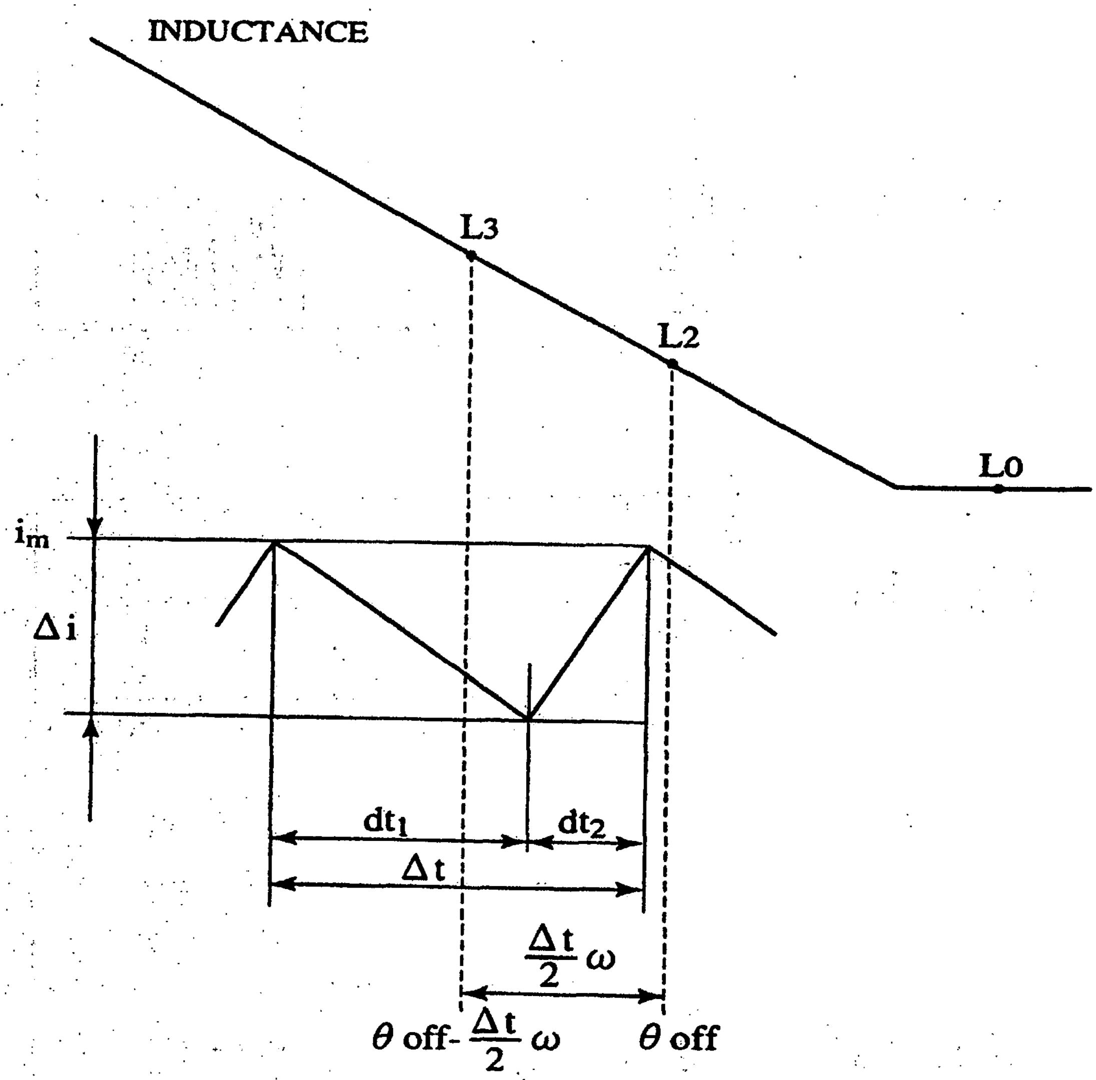
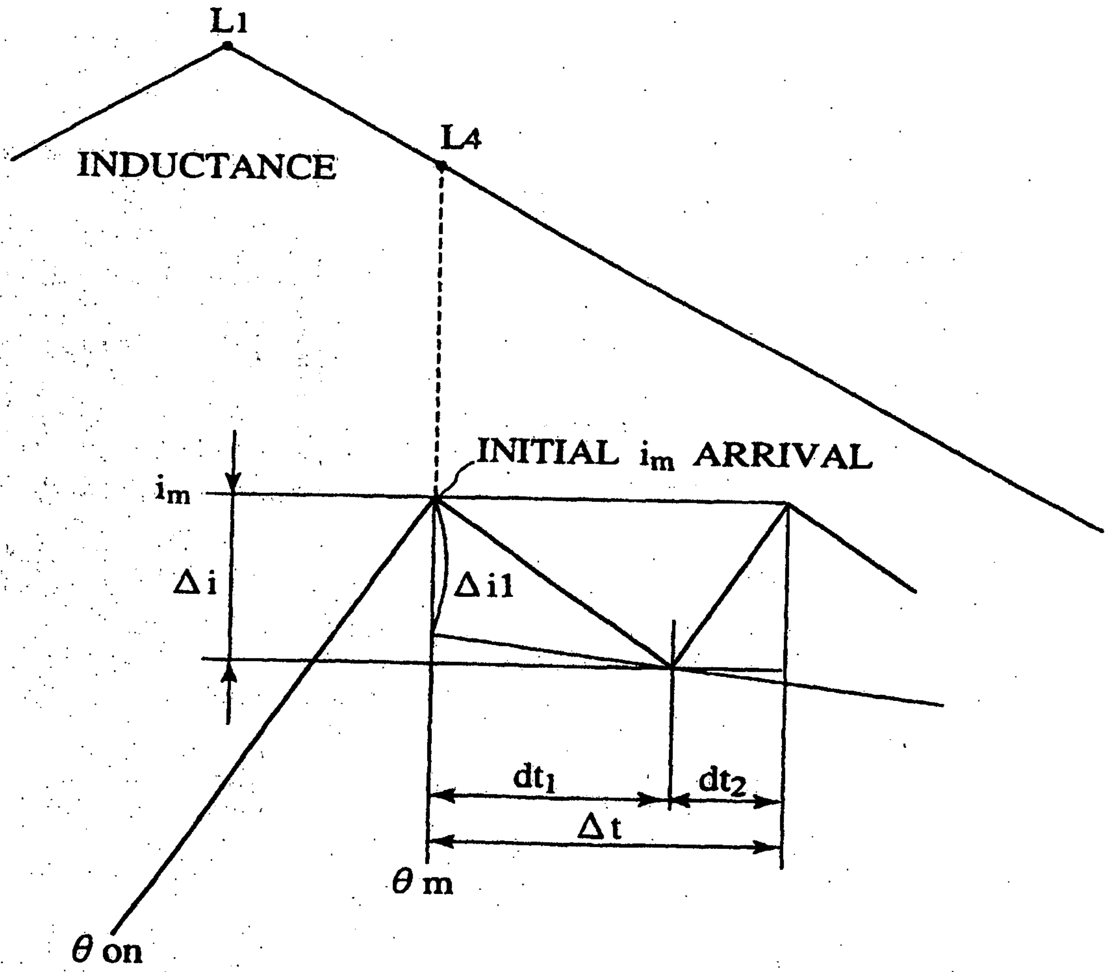


FIG. 9



INDUCTANCE
L3
L2
L0
i_m
Δi
dt_1
dt_2
Δt
$\frac{\Delta t}{2}\omega$
θ off- $\frac{\Delta t}{2}\omega$
θ off

FIG. 10


L1
INDUCTANCE
L4
INITIAL i_m ARRIVAL
i_m
Δi
$\Delta i1$
dt_1
dt_2
Δt
θ m
θ on

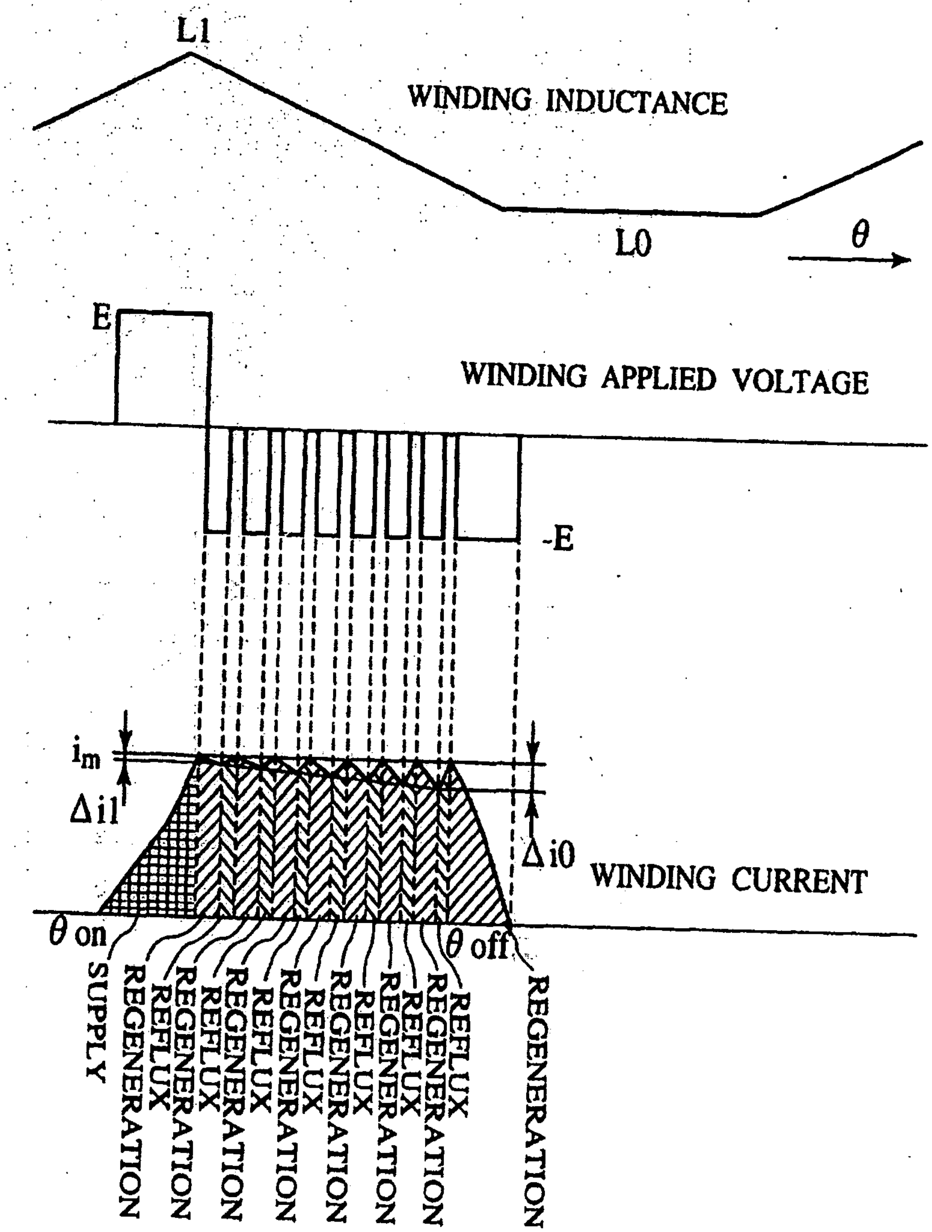


FIG. 11A

FIG. 11B

FIG. 11C

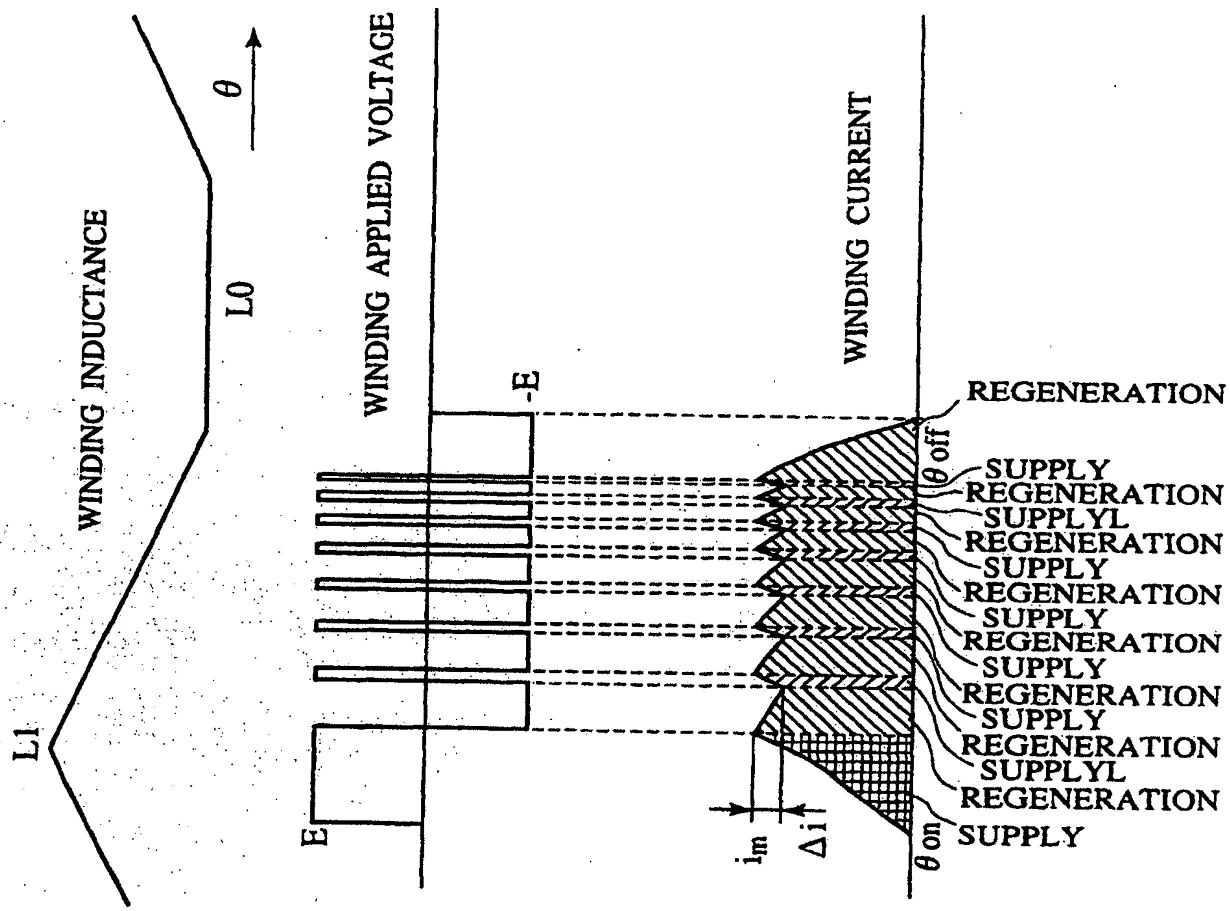


FIG. 12A

FIG. 12B

FIG. 12C

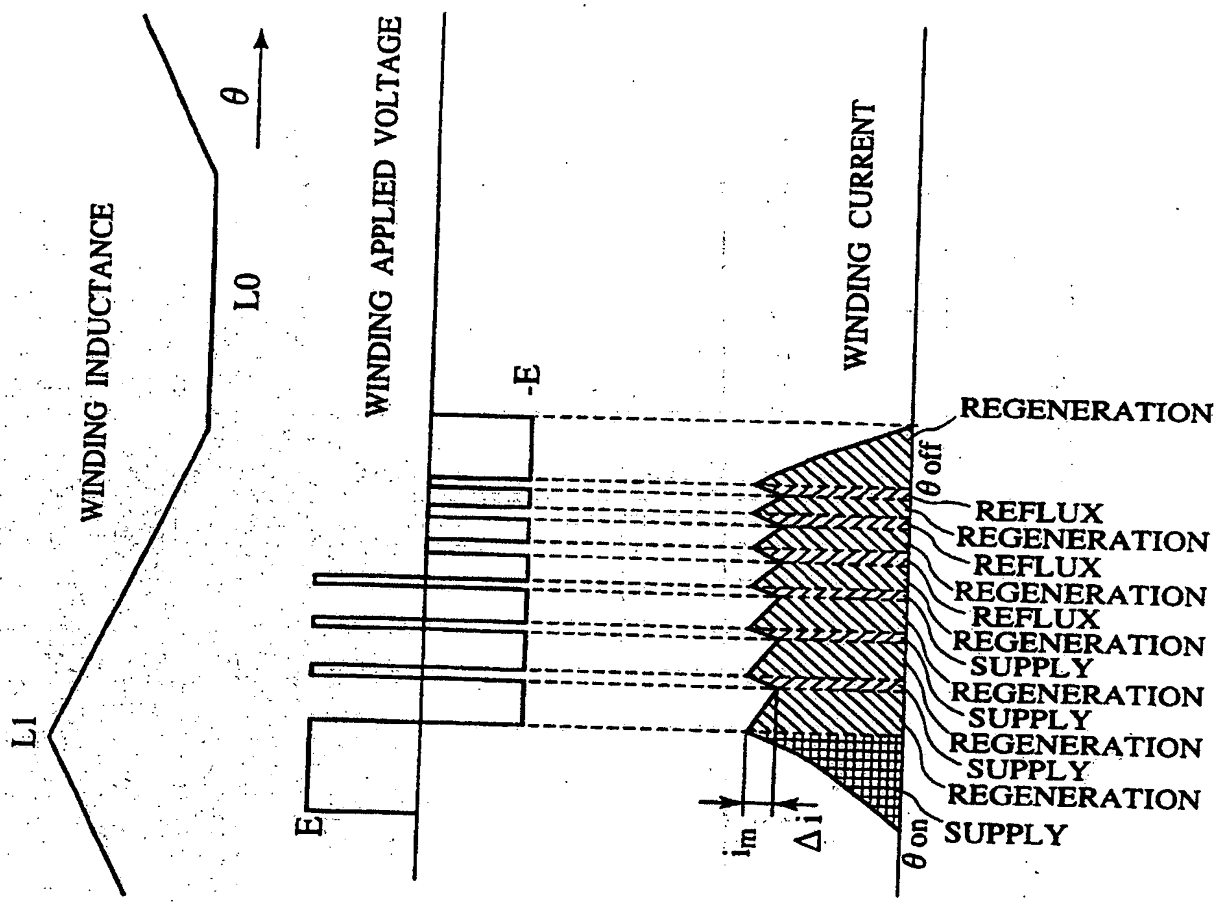


FIG. 13A

FIG. 13B

FIG. 13C

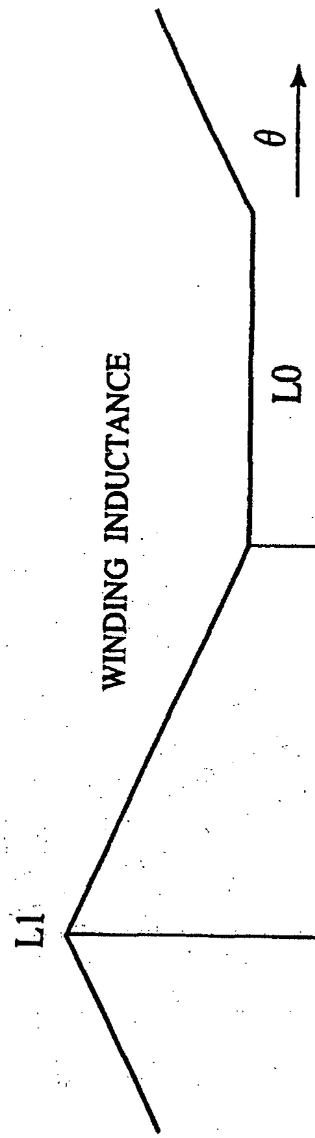


FIG. 14A

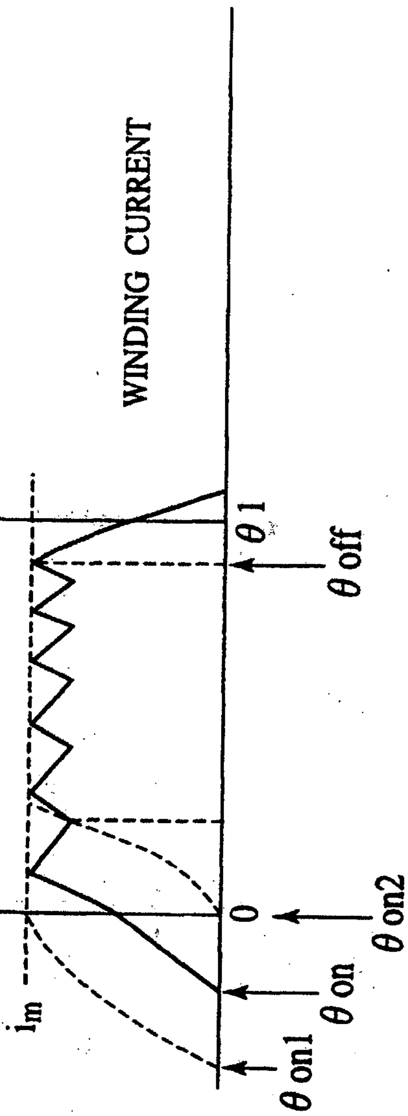
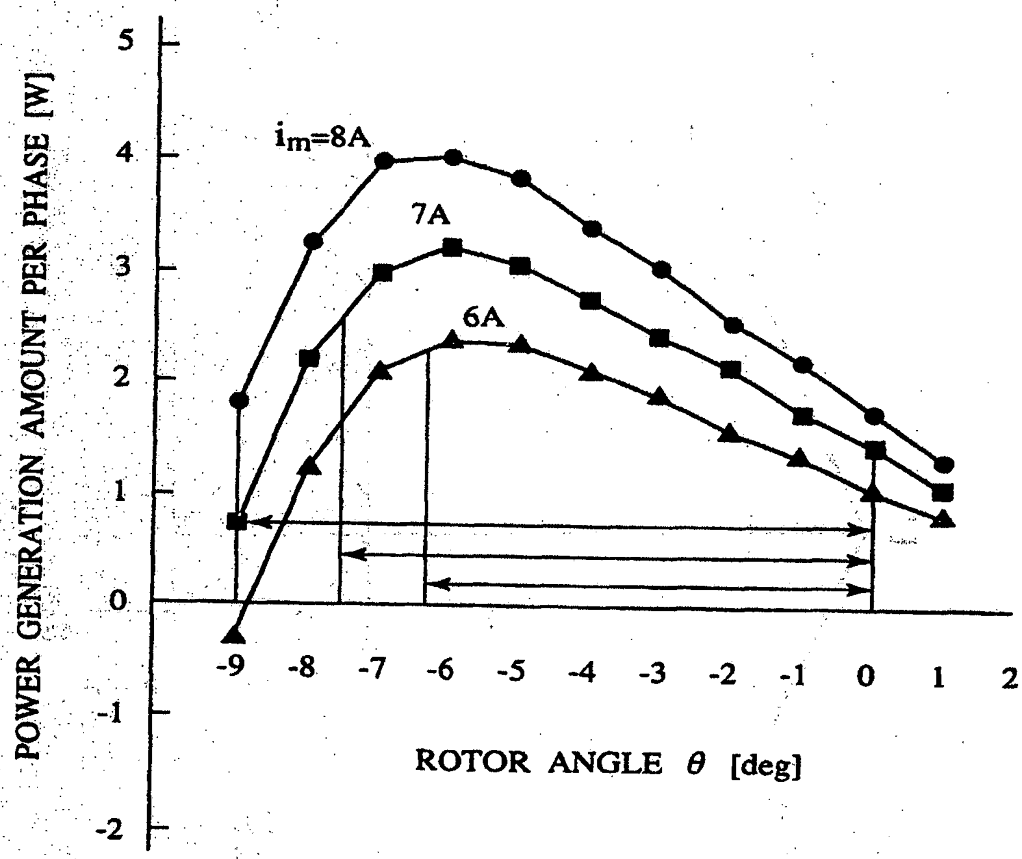


FIG. 14B

FIG. 15



POWER GENERATION AMOUNT PER PHASE [W]
5
4
3
2
1
0
-1
-2
i_m=8A
7A
6A
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
1
2
ROTOR ANGLE θ [deg]

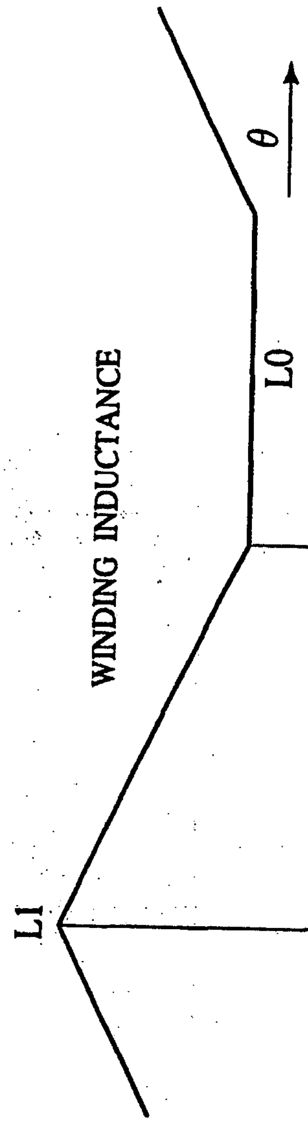


FIG. 16A

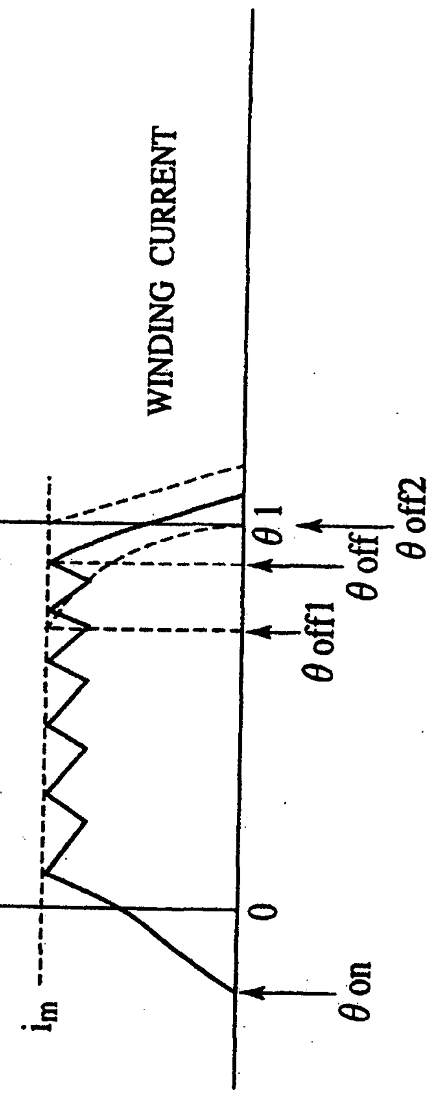


FIG. 16B

FIG. 17

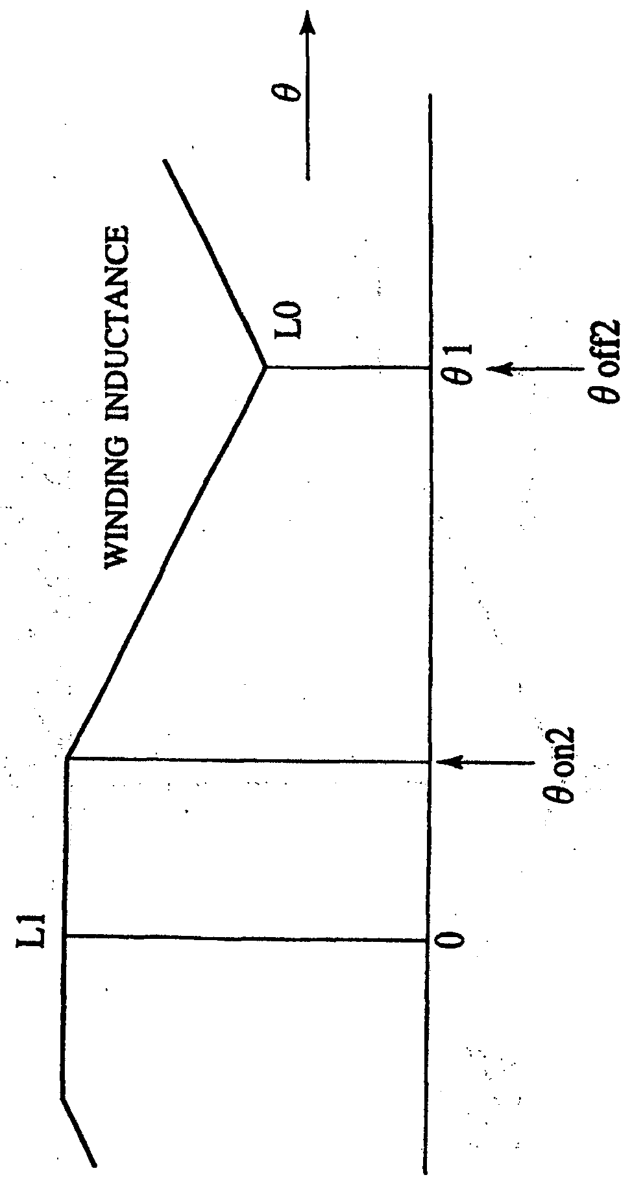
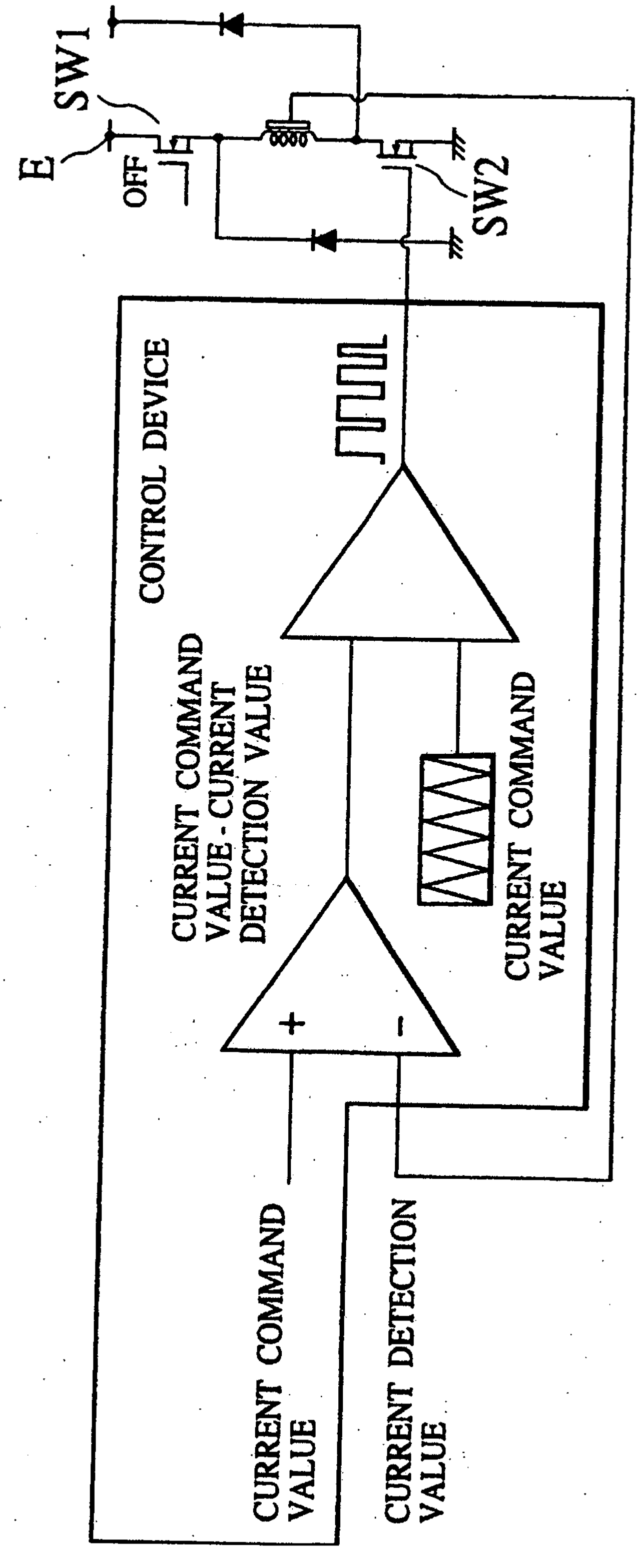


FIG. 18


E
SW1
OFF
SW2
CONTROL DEVICE
CURRENT COMMAND VALUE - CURRENT DETECTION VALUE
CURRENT COMMAND VALUE
+
-
CURRENT COMMAND VALUE
CURRENT DETECTION VALUE

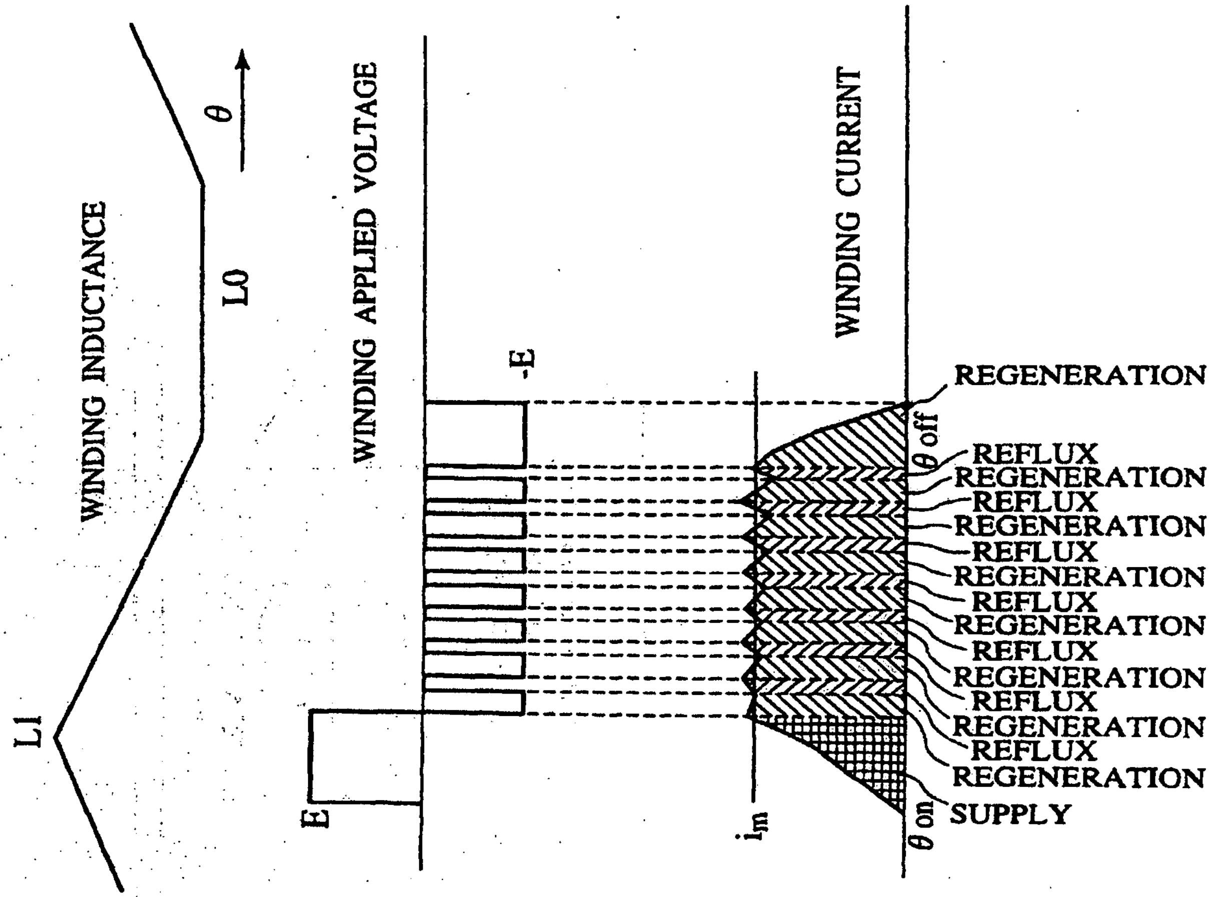


FIG. 19A

FIG. 19B

FIG. 19C

(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 1 067 670 A3

(12) EUROPEAN PATENT APPLICATION

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26.09.2001 Bulletin 2001/39

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(22) Date of filing: 05.07.2000

(51) Int Cl.7: H02P 7/05

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17.03.2000 JP 2000075489
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(54) Controlling method forswitched reluctance motor method and motor having a low peak current

(57) The SR motor (1) includes a stator (3) having a plurality of salient poles (3a), windings (C) wound around the plurality of salient poles (3a) and generating magnetic fields in the plurality of salient poles (3a), and a rotor (2) having another plurality of salient poles (2a), a number of the salient poles of the rotor being determined depending upon a number of the salient poles of the stator. A supply mode for supplying power from a power supply to the windings (C), a reflux mode for setting both terminals (T1, T2) of the windings (C) to an identical potential, and a regenerative mode for recovering electromotive force generated in the windings (C) into the power supply are executed as the rotor (2) rotates. The reflux mode and the regenerative mode are preferably repeated in a period during which the inductance of the windings (C) is reduced as the rotor (2) rotates.

FIG. 5A

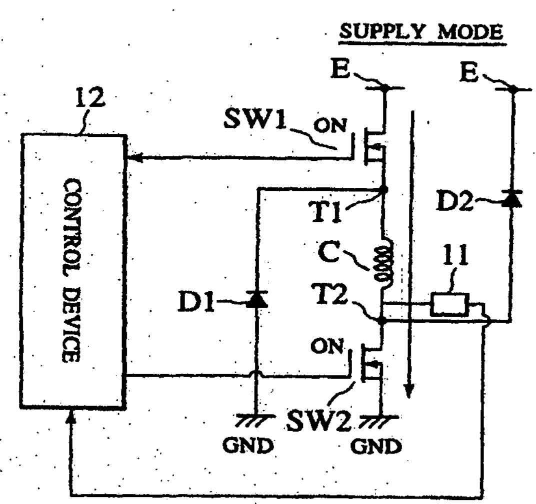

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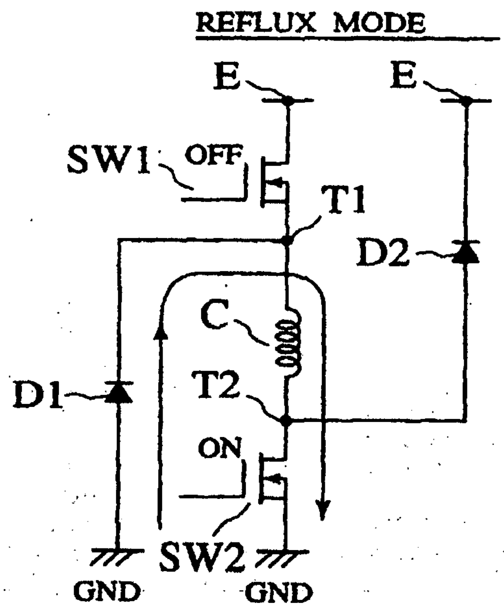
FIG. 5C



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EUROPEAN SEARCH REPORT

Application Number
EP 00 30 5642

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.7)
X Y	WO 99 13563 A (SUNDSTRAND CORP) 18 March 1999 (1999-03-18) & US 5 936 386 A (HEGELUND W.) 10 August 1999 (1999-08-10) * abstract; figure 7 *	1-6,40, 41,49 7-9, 20-22, 42,43,50	H02P7/05
Y	US 5 166 591 A (STEPHENS CHARLES M ET AL) 24 November 1992 (1992-11-24) * abstract; figures 2,3 *	7-9, 20-22, 42,43,50	
P,X	EP 0 948 125 A (AISIN SEIKI) 6 October 1999 (1999-10-06) * abstract *	1	

TECHNICAL FIELDS SEARCHED (Int.Cl.7)
H02P

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	6 August 2001	Wansing, A

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06-08-2001

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		US 6157160 A	05-12-2000

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